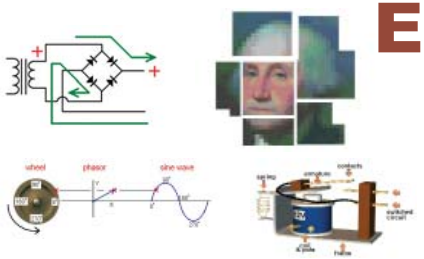


EM5 – Comprehensive

by Karl Eilers

EM5 will cover the following concepts:

- Soldering, desoldering and tools
- Electrical conductors
- Motors
- Generators
- AC power generation and distribution
- Circuit controls
- Circuit protection devices
- Interfacing electronic equipment levels
- Interfacing electronic equipment cables and connectors
- Technician work procedures

Give Your Students the Power to Succeed with the Online EM-Series Study Guides

The EM-series of study guides give students the knowledge they need to qualify as entry-level technicians, and provides the necessary foundation for further studies in specialized fields. The study guides are closely coordinated with the ETA competencies and exams. Each study guide builds on the one before it. Together they form an efficient, no-time-wasted path to knowledge and certification.

The basic goal of the study guides is the same as the goal of the EM certifications themselves: each milestone on the way to eventual mastery is useful in and of itself, giving students immediately useful information and permitting them to earn graduated certifications commensurate with their growing knowledge.

Study Guide for ETA-International EM5 COMPREHENSIVE

by Karl Eilers

Welcome to the fifth of the ETA EM training modules, Comprehensive. This is a grab-bag study guide where we discuss important topics that didn't fit into the first four study guides. We'll study types of wire and cable, typical interconnections, tips about terminating cables and how to solder and desolder components on circuit boards.

Much of this chapter is devoted to motors, generators, and the AC power distribution system. This wasn't put in any of the previous study guides because it draws on DC, AC, analog and digital technology together.

Not all of a technician's job is related to electronics. Techs must also keep records, deal with fellow employees, deal with the public, do invoicing and billing (or provide the necessary paperwork to the invoicing and billing department) and look out for the company's interests in ways that go beyond electronics. The last chapter covers these issues.

Contents

1. SOLDERING, DESOLDERING AND TOOLS
2. ELECTRICAL CONDUCTORS
3. MOTORS
4. GENERATORS
5. AC POWER GENERATION AND DISTRIBUTION
6. CIRCUIT CONTROLS
7. CIRCUIT PROTECTION DEVICES
8. INTERFACING ELECTRONIC EQUIPMENT-LEVELS
9. INTERFACING ELECTRONIC EQUIPMENT-CABLES & CONNECTORS
10. TECHNICIAN WORK PROCEDURES
11. REVIEW

PRACTICE EXAMS

ABOUT EM1-EM5 AND THE CETa CERTIFICATION

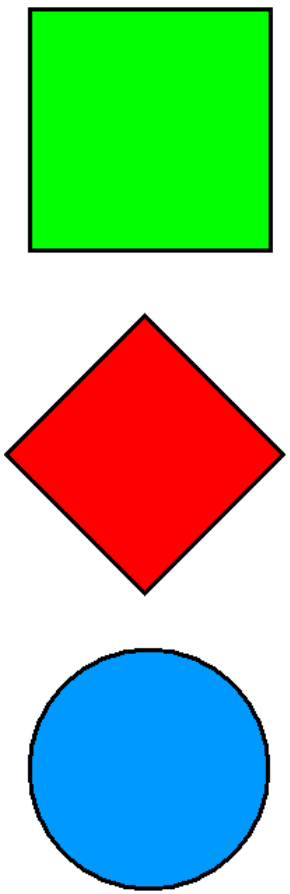
A student who completes and passes the exams for EM modules 1-5 automatically qualifies for the basic-level technician certification, the **CETa** or **Certified Electronic Technician, associate**. This certification indicates that the person holding it has enough training to enter the electronic field as an entry-level technician.

The CETa is valid for four years, after which it expires. Normally, during those four years, the CETa holder receives advanced training in a specialty like fiber optics or renewable energy, and then takes the ETA exam in this specialized field to receive a journeyman certification.

ASPECT RATIO ADJUSTMENT

For many of the illustrations in this study guide, it is important that the dimensions and angles be correct. The green shape should appear as a perfect square, not a rectangle. The red diamond should have 90-degree corners. The blue shape should be a circle, not an oval.

If these shapes are not what they should be, please adjust your display settings before you begin this study guide.



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EM5 Chapter 1
SOLDERING

Objectives of this chapter:

- *explain how solder bonds conductors together*
- *name commonly used alloys and their melting points*
- *name types of flux and which should not be used in electronic work*
- *describe the purpose of flux*
- *discuss necessity and procedure for removing flux*
- *explain how to avoid burned black residue*
- *describe the parts of a soldering iron system*
- *describe the process and reasons for tinning tips*
- *discuss tip types and shapes and how to maintain them*
- *discuss soldering guns, advantages and disadvantages*
- *describe in detail the process of making a solder connection*
- *explain why it is good to work quickly*
- *explain how to visually identify a bad joint*
- *discuss special precautions when soldering CMOS*
- *discuss desoldering techniques*

Every tech needs to know how to solder. Even if you're planning a career path that usually doesn't require it, you'll never avoid it completely.

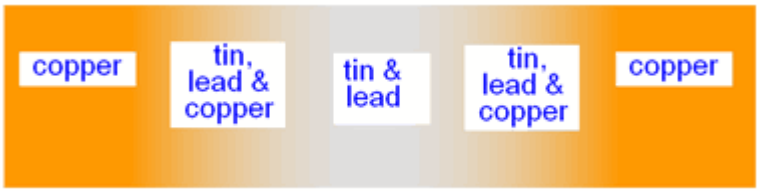
The job of soldering boils down to two considerations:

First, making a good, reliable joint. It's quite possible to make a solder joint that looks perfect but is unreliable.

Second, not damaging anything in the process. A soldering iron is more than hot enough to burn fingers, melt carpet, char wood, and set paper or cloth on fire. Stray solder blobs can short out circuitry and poor technique can ruin components.

Solder is a metal alloy that fuses wires, component leads and PC board traces together to form a continuous, conductive electrical path. I stress the word “fuses.” The most important thing to understand about soldering is that solder doesn't just stick to the surfaces like masking tape. There is actual metal alloying going on. If we're soldering, say, two copper wires together, the solder **wets** the copper surfaces and a small amount of copper dissolves into the solder, so there's a transition area where the solder and the wires become part of each other. Essentially, the wires and solder become a single piece of metal whose chemical composition is different in different places.

This fusing accounts for a good solder joint's strength and reliability. If it doesn't happen – if the solder just sits on the surfaces of the wires – the joint will be unreliable and stress or flexing will break it.



ALLOYING OF COPPER AND SOLDER

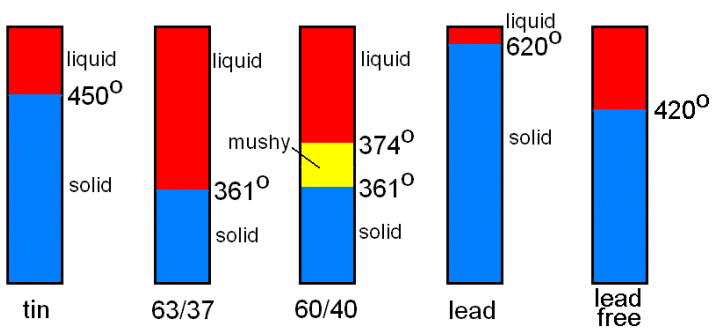
SOLDER ALLOYS

An alloy is a chemical mixture of two or more metals. The traditional solder for electronic work is a **tin-lead alloy**. This alloy has the interesting property that it melts at a lower temperature than either of the metals it's made from. Tin melts at about 450^{O}F; lead melts at about 620^{O}F. But the lowest-melting tin/lead alloy melts at only 361.4^{O}F. This is called **eutectic** solder, and it's an alloy of 63% tin and 37% lead.

Pure tin or pure lead, and their 63/37 alloy, have a single transition temperature between liquid and solid states. Alloys with other percentages of tin and lead have a state between liquid and solid that might be called “mushy.” As solder is cooling, during the time when it's in the mushy state, it is crucial that the work be held still. If it is flexed, you'll wind up with a crumbly texture that can easily be broken and is electrically unreliable.

One example of a non-eutectic alloy is **60/40** solder, the traditional solder most commonly used for electronics, which is 60% tin and 40% lead. This alloy is liquid above 374^{O}F, solid below 361^{O}F and mushy between 361 and 374 degrees.

Traditional solder is being replaced by lead-free varieties. This is being pushed along by **RoHS**, the **Restriction of Hazardous Substances Directive**, which became effective in Europe in 2006 and is making inroads in the USA. One popular lead-free solder is an alloy of tin, silver and copper which melts at about 420^{O}F. In general, lead-free solder melts at higher temperatures than solders containing lead, which makes good soldering techniques even more important. Lead-free solder is also more prone to **whiskers**, which are tiny strands of metal that are left behind when you're done soldering if your technique isn't good. These can be so small they're almost invisible, and can cause short circuits that are difficult to locate.



Lead-free solders are up to 99.5% tin, because tin is so good at wetting. If soldering were a party, tin would be the person with the big smile who mixes easily and instantly bonds with everybody. In fact, wires, PC traces and component leads are often **tinned** at the factory, plated with a thin coating of tin, to facilitate soldering and protect against oxidation. If you anticipate that it will be difficult to make a particular connection, you can make things easier by tinning each of the parts beforehand, as described below.

I would suggest learning to solder with standard tin-lead solder first. It's more forgiving, and you get a visual indication of whether you've done it correctly: a good solder joint is shiny, a bad one is dull. With most lead-free solders, all joints are dull.

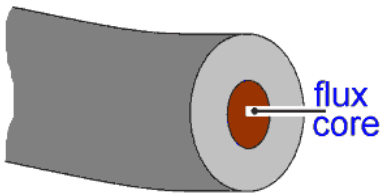
Keep in mind the "four Ts" that lead to success:

- The right **tip** for the job
- Properly **tinning** the tip
- The right **temperature**
- The right **timing**

And, be sure you hold the work still until the solder has solidified.

SOLDER FLUX

Most metals develop enough surface oxide within seconds to prevent clean soldering. For this reason, a **flux** must be applied to the joint during soldering to reverse the oxidizing process and present a pure metal surface to the solder. Solder intended for electronic use has a flux paste inside; the solder is manufactured in the shape of a tube, with flux filling the core. Besides the convenience of not having to apply flux in a separate step, flux-core solder also guarantees that the flux will be applied exactly where and when it's needed.



There are essentially two kinds of flux, acid and rosin. *Acid-core solder is for metalworking; it should never, ever be used in electronic work*. It is impossible to clean away the acid completely, and the residual will corrode the circuitry over time. Only "**rosin**" flux (from tree sap originally, other chemicals with the same function today) is acceptable.

After soldering is completed, a bit of flux is left on and around the joint. In many service/repair situations, this does not need to be removed, but if sensitive or high-density circuitry is involved, the flux should be cleaned away. Rosin flux, despite its waxy composition, can absorb moisture and become slightly conductive, which can mess up circuit operation. In a manufacturing situation, flux should always be removed. Electronic supply companies sell solvents specially made for the purpose.

An issue has arisen over these solvents. The environmental protection people are trying to reduce the use of solvents wherever possible. For this reason, traditional rosin flux is being replaced by newer water-soluble fluxes that can be simply washed away with water and detergent. Needless to say, these fluxes *must* be removed to prevent them from absorbing water from the atmosphere and creating conductive paths that aren't supposed to be there.

Some companies make “no-clean” flux, which leaves little residue. A nice feature, but the downside is that, in those cases where you do need to remove the flux, no-clean residue is harder to remove than regular flux. Try it and see if you like it; my own preference is for regular flux.

If you need more flux than what's in the solder core, you can get liquid flux in a bottle with a brush. Anyone who does a lot of soldering should keep some on hand. Beware of general-purpose flux in a metal can; even though it's rosin flux, it may contain a little acid to “activate” it. Stick with flux that's specifically made for electronic use. I use General Cement 10-4202, which is liquid at room temperature. Keep the cap securely screwed on; flux loves to leak and it makes a real mess. If you spill it, don't waste your flux remover cleaning it up. Use lacquer thinner.

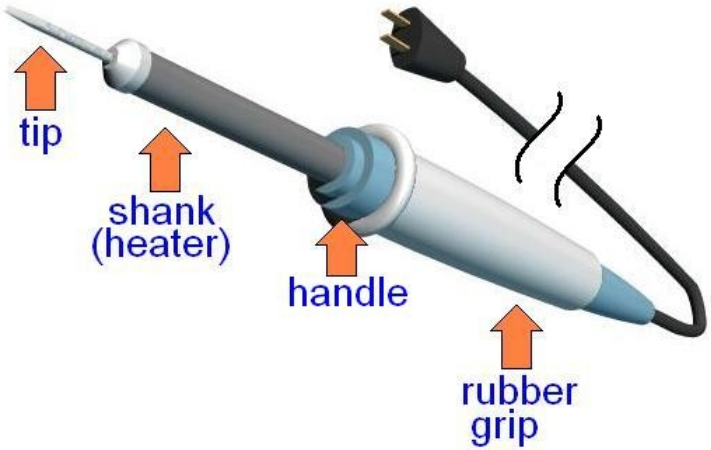
In the process of soldering, flux gets on the tip of the soldering iron, and sits there and cooks. This results in a black, carbonized mess on the soldering tip that must be frequently removed by wiping the tip on a damp sponge made for soldering.. Failure to clean the tip results in the black gook being left behind on the joint. A blackened connection is one of the calling cards of a sloppy technician.

Cleaning flux off the board after soldering involves spraying on the appropriate liquid, either water or solvent, scrubbing with a stiff non-metalic brush, and spraying again to rinse. You'll often have to repeat these steps to get a good clean board.

SOLDERING IRONS

As an electronic tech, you're a wizard of sorts compared to the average non-technical person. A wizard should have a wand. Yours is the tech's general-purpose soldering iron, the **soldering pencil**. You use it to transfigure parts into working circuits. Is my Harry Potter fixation showing?

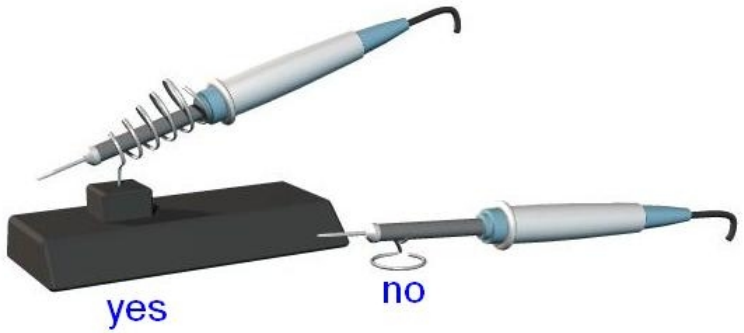
The heart of a soldering pencil is the shank containing the heating element. A replaceable tip is attached to one end, which transfers heat from the heating element to the joint being soldered. The other end is attached to an insulating handle.



A soldering pencil system has three pieces: the pencil, its holder, and a damp sponge. If you don't have all three on hand, you're not ready to solder.

The holder gives you a safe place to put the iron when it's not in your hand. Holders take the form of a mostly-open wire mesh or spiral so as to not draw off all the iron's heat. Some holders don't have very stable bases. If you have one of those, screw it to something so it can't tip over.

Cheap holders are just a little piece of wire or sheet metal with a notch to set the iron in. These aren't anywhere near stable enough to be safe. If you bump the iron, or even its cord, it will fall off the holder. Even high-quality irons often come with crummy holders. If you have to pay extra to get one that fully encircles the shank, do it.



The sponge must be organic, not plastic or rubber. It sits in a dish that acts as a water reservoir. Before you start soldering, dampen the sponge. When you're soldering, you wipe the iron's tip on the sponge after every few joints to keep it clean.

Soldering irons for electronic work are generally 15 to 60 watts. The smaller ones are good for fine work, while the larger ones are needed when you're soldering something with some mass, like a PL259 coax connector.

If you try to use a cheap hobbyist iron, you will never become as good at soldering as you want to be. There's a saying that “a poor worker blames his tools” for the poor quality of his work, but on the other hand, one of the reasons a good worker does good work is because he/she doesn't use junk tools. A tech needs to own a quality iron.

The ultimate is a **temperature-controlled** iron, which contains an electronic circuit to control the tip temperature. The least expensive ones simply vary the power via a knob, but better ones are thermostatically controlled, so they stay at a set temperature all the time. You can get an iron with a knob on the side to set the temperature for a mere $20 from manufacturers like Xytronic, so there's no reason to put up with something inferior.

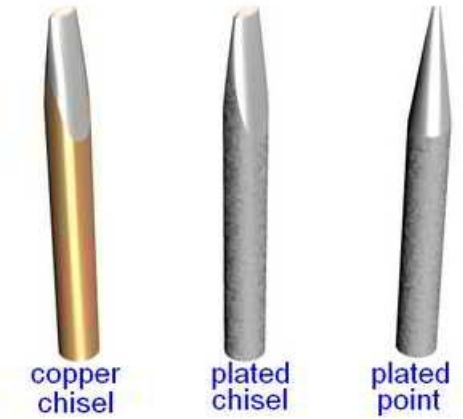
If you do a lot of workbench soldering, you should invest in a **soldering station**. This is a box with power supply, temperature control knob and (usually) temperature meter, with the wire-mesh holder and a place for the sponge on top. The power may be as high as 60 watts. There's no reason to fear that this will be too much power, because you can dial it down. The one I use cost nearly $100, and It's one of the best investments I ever made.

SOLDERING IRON TIPS

The replaceable tip feature permits the tech to keep an assortment of tips for different kinds of soldering jobs. The two most common shapes are a point and a small blunt chisel. Points are good for fine work, while the chisel shape provides a flat surface you can lay against a joint to quickly transfer a lot of heat. Both types come in a variety of sizes. As you gain experience, you will come to have one or two favorite sizes in each shape. I can't tell you which ones to choose because it's a matter of personal preference. If you do a great deal of soldering, it may be easier to buy several irons instead of switching tips all the time. Using a temperature-controlled iron makes this less necessary, as a single tip can be adapted to do of jobs from medium-small to medium-large, by simply adjusting the temperature.

Soldering tips are made of copper, not only for ease in tinning but because copper is a good heat conductor. Copper has a problem, though. I mentioned that solder alloys with the copper wires in a joint. It also alloys with the copper in the soldering tip. Over time, this eats away the tip, leaving a deep pit. Every now and then, you'll have to take a file and scrape away enough material to get back to a flat surface. Eventually the tip will be used up and you'll have to replace it.

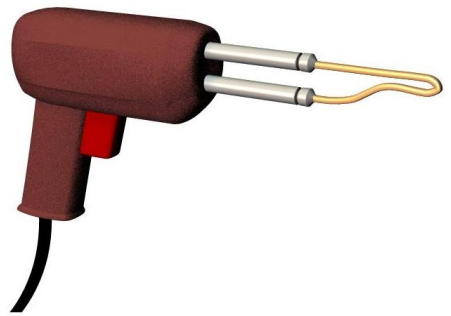
The copper-tip problem can be avoided by using iron-plated copper tips. These are a bit more expensive but well worth the added cost, as plated tips remain in new condition for a long time. My humble opinion: a professional tech should not use anything else.



Even when an iron is not actually soldering and getting flux on it, a hard black crust will build up on the tip as it sits in its holder and cooks the air. With a copper tip, this can be removed with a file, but you should never use a file on a plated tip. After all, the advantage is lost if you file the plating off! When the tip is cool, use an abrasive cloth or sponge to clean it. On the other hand, if you're wiping the tip on the wet sponge as often as you're supposed to, the black crust will not build up.

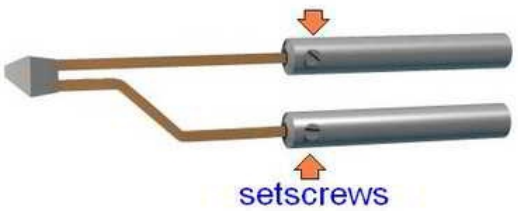
SOLDERING GUNS

There's another kind of soldering tool that works on a different principle. The **soldering gun** is essentially a step-down transformer. The primary plugs into a 117VAC outlet and a low voltage is induced in the secondary, which is essentially a single turn of monster-gauge wire. The soldering tip, which is connected to the secondary, shorts it out. The resulting current, on the order of 100 amps, is high enough to heat the tip to several hundred degrees.



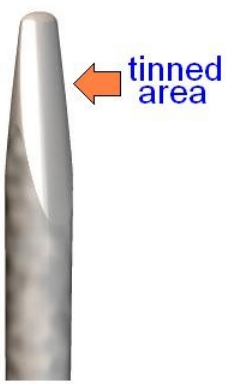
Solder guns are not intended for fine work. They're big, clumsy, weigh a lot and are typically rated at power levels of 100 to 500 watts. I would never recommend them if it were not for one beneficial characteristic: they heat up and cool down quickly. A soldering gun has a trigger switch. The tip heats when you squeeze the trigger, and then when you release the trigger, it cools down in seconds. Thus a soldering gun sitting on a desk or carpet is not a fire hazard. This is especially important if you work outside the shop, on a customer's premises. Many employers try to arrange work procedures so there's no soldering of any kind at the jobsite, because the risk of fire or other damage is so high. Rule of thumb: pencil in the shop, gun in the field. That may not be practical if the field soldering you do is too fine or delicate for a gun.

If you use a gun, keep several tips on hand. Once a tip starts getting pitted, usually on the underside near the front, a hot spot develops that quickly eats the tip all the way through.



The principal maintenance issue with guns is keeping the electrical connections tight. The tips are secured either by setscrews or by a collar that cranks down against a bent part of the tip. These have a habit of coming loose, and then most of the heat is developed at the connections instead of the front of the tip where you need it. Every day, before you start using the gun, check the connections for tightness.

TINNING THE TIP



The very first time a new soldering iron is used, you must melt a bit of solder and spread it around on the tip. This is called **tinning the iron**, and it serves a dual purpose. First, it keeps air away from the tip so it can't oxidize. Second, when soldering, it helps transfer heat to the joint. Tinning must be done as soon as the tip is hot enough to melt the solder, because at that temperature oxidation occurs very quickly. If you wait even a minute too long, the tip will be covered with oxide and it won't wet.

If you're using unplated copper tips, any time you file the tip, you expose bare copper so you'll need to re-tin. It's best to do the filing when the tip is cold. Every day, before you turn the iron on, check the tip to see if it needs filing. While you're at it, check to see that it isn't loose in its holder. This should be part of your morning routine like brushing your teeth.

MAKING A SOLDER JOINT: TEMPERATURE AND TIMING

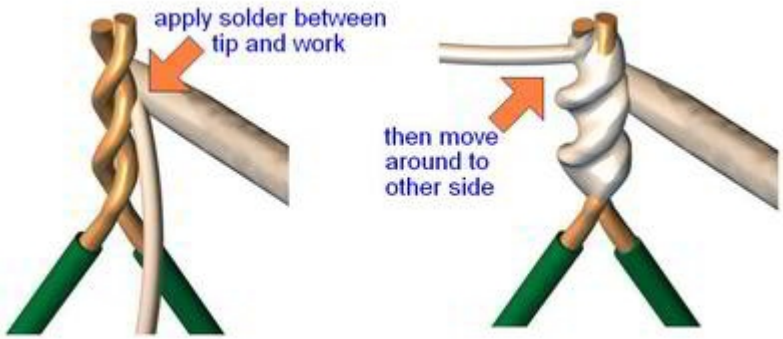
The essential problem with soldering is that it involves temperatures that are high enough to destroy the components being soldered. Also, too much heat for too long can melt or burn wire insulation and cause PC board traces to come loose. So, when you're soldering, you have to heat the work just long enough to create a good bond, but not so long that the heat has time to travel up the lead and damage the component. In other words, soldering is a matter of *timing*, among other considerations.

You'll need practice to develop a knack for heating up a joint and applying solder as quickly and efficiently as possible, so you can remove the iron before damage occurs.

Solder must *flow*. It must wet the surfaces of all the wires, the PC board trace, solder lug, etc that are part of the connection. To get a good idea how solder should flow, take a pair of wires, twist them together into a joint, and then apply a drop of light machine or salad oil. Note how the oil flows over the surfaces, completely coating them and wicking its way into every crevice. That's what solder should do.

To get this to happen, the joint must be hot enough for the wetting and wicking action to occur. If you just melt some solder onto the iron and then apply it to the joint, it will refuse to wet, both because the joint isn't hot enough and because the flux on the tip burns off before it can do its job. Instead, you must heat up the joint and apply the solder *to the joint*, not the iron.

Everybody has their own technique. My practice is to apply the solder for just a moment at the point where the iron touches the joint. The instant I see a little solder flowing, forming a heat bridge between the iron and the joint, I move the solder around to the other side of the joint. In this way I can usually get on and off in a few seconds.

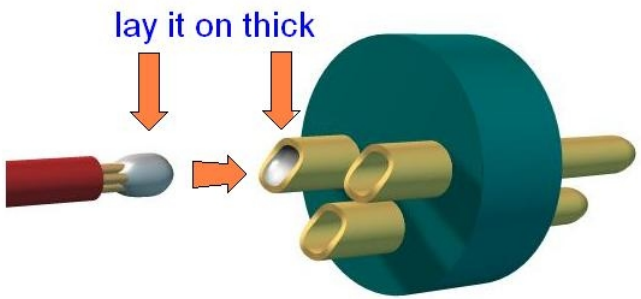


When you're soldering to a PC board or solder lug, place the iron where it touches all components, so it can heat them all at once. It's common for beginning techs to make defective joints because one part or another didn't get hot enough to melt solder, and is insulated by an air gap or thin layer of flux. It can be really difficult to diagnose the resulting malfunction because the joint *looks* fine.

Sometimes you'll need a third hand, and you'll be tempted to hold the solder in your mouth. If you're using tin/lead solder, don't do this, okay? Lead is a poison. Just don't, not now, not ever. I admit do doing it in the past, when I was young and foolish, which is probably the reason for the third eye in the middle of my forehead and the fact that I set off fire alarms when I sneeze. If you're really deft, you can develop the ability to hold a wire between two fingers and solder between two other fingers of the same hand.

Or you can take the sensible route and keep a portable vise handy. There are also jigs that have alligator clips on flexible arms, like crabs. In a pinch, you can make one out of an alligator clip and a coat hanger.

When necessary, you can solder by tinning both of the parts and then **sweating** them together. In this case we're not talking about a thin tin plating. Melt on as much solder as you'll need; then you won't have to add more solder when actually making the connection. This gives you just three pieces to deal with, the iron and the things you're soldering. Put one piece in the vise, hold the other with one hand and the soldering iron with the other hand. This technique is especially useful when connecting wires to the solder cups of connectors; the cups should be pretty much full of solder.

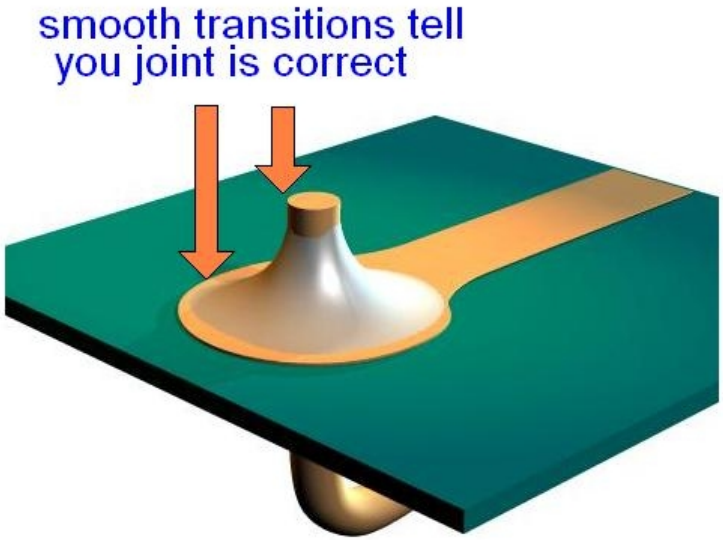


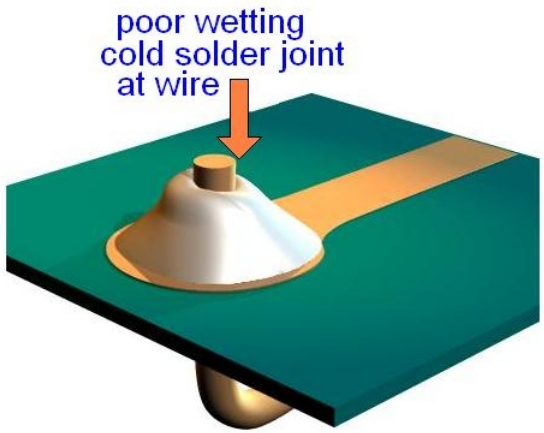
Try to get the connection right on the first try. Some techs reheat a joint several times, trying to get something that looks perfect. It's true that your joints should look good, but it's more important that they work. Every time you re-melt the solder, the electrical resistance goes up and the strength goes down. Every time, you're increasing the risk of damaging components. Every time, you're more likely to cause traces to come loose from the PC board (they're just held on with glue, after all). Practice until you only need to do a joint once.

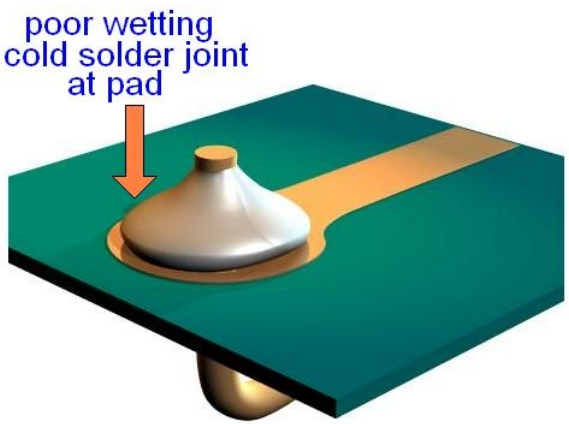
If you're having trouble making a joint and you've burned off all the flux, first let the work cool down. Then inspect the joint – why are you having trouble? Maybe the joint isn't clean enough, maybe you only applied the heat to one part, and it isn't transferring. When you make your second attempt, add a little more solder or brush on some flux to freshen the joint.

The last step is to carefully inspect the joint from all angles. You should be able to visually verify that solder has coated every single wire, pad, solder lug etc, that's part of the joint, and that there aren't any flyaway wire strands that could short to something else. If possible, flex each wire; if there's any movement at the joint, you've screwed up. Inspection will go more quickly once you gain experience; you'll “feel” that you've done it right (or not) almost without looking.

If the solder has properly wetted the work, the shape of the solder will be concave, not bulging, and the transition areas between solder and work will be smooth, like an ocean meeting a sandy beach.







HOW DO I KNOW WHEN I'VE APPLIED TOO LITTLE HEAT?

Knowing how long to heat the joint is a “sixth sense” that develops with practice. The giveaway that you haven't applied enough is a joint where the solder has not completely flowed. If it's sitting in a blob, you've made a **cold solder joint** and you need to redo it. Remember, solder should behave like light oil. Oil does not sit in a lump.

HOW DO I KNOW WHEN I'VE APPLIED TOO MUCH HEAT?

Unfortunately, there's no reliable answer to this one. Many things, especially semiconductors, can be damaged without any outward sign of stress. This is something that can only be learned the hard way; you'll know better next time.

However, you know something's surely wrong if you see parts sweating, steaming or discoloring, or wire insulation melting. When soldering to a PC board, a trace should never come loose and the board should never become discolored.

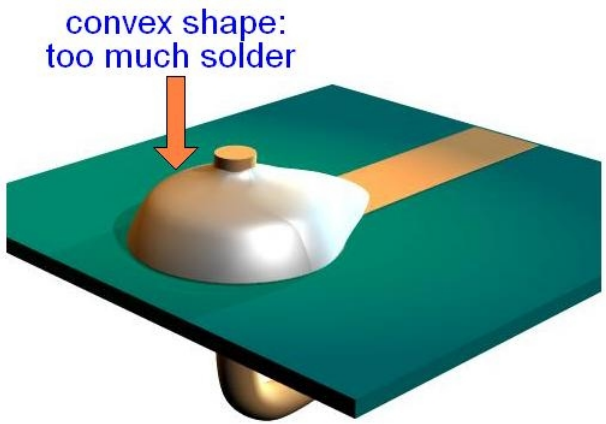
One of the best reasons for making a joint quickly is that it takes time for heat to travel up a wire or component lead. If you're fast, you'll heat *just the joint* hot enough to melt solder. By the time heat starts to spread, it's already dissipating. For the sake of speed, I set my iron relatively hot, around 750^{O} F, but at that temperature you need a really deft touch. Practice with different temperatures and see what works for you.

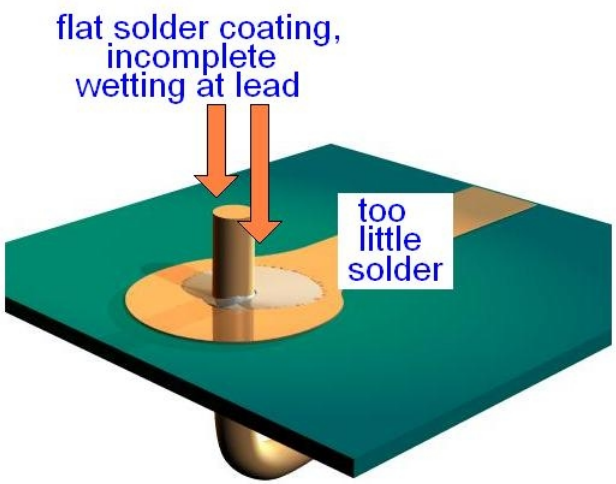
Sometimes you find yourself in a situation where you have no choice but to apply heat for a long time to a lead of a component that could be damaged. You can get soldering **heat sinks / heat shunts** that clip onto the lead between the component and where you're soldering. Don't go out and buy them until you're sure you need them, because a person who is skilled at soldering doesn't use them very often. In a pinch, grab the lead with a longnose pliers. Use a rubber band on the handles to keep it clamped on so your hands are free. An excellent option is the kind of surgical clamp with a toothed part that automatically locks the clamp until you release it. Standard alligator clips aren't very useful as they don't draw off enough heat to protect the component.

HOW MUCH SOLDER

This is not so much an electrical issue as a mechanical one. Too little means the joint is weak. Too much means you piled on a lot of unnecessary heat when making the joint. Aim for smooth concave surfaces. Again, this is just a matter of practice. Get a piece of junk equipment and melt and remelt the joints until you've mastered it.

Lead-free solder doesn't flow as well, so you won't get perfect joints like the first example on page 11. You'll use a little more solder and PC board connections will look like little Hershey kisses. (TM)





SPECIAL METALS

In some high-buck gear, you'll find terminals made of silver. Tin-lead solder will quickly dissolve them. Use solder with 3% silver in it, which you may be doing anyway if you're trying to be green.

Phosphor-bronze is often used for springy things like switch parts. It can be soldered, but doesn't like it. The metal develops a very hard insulating oxide that flux won't remove. It must be scraped clean with a file just before soldering; then use lots of flux and lots of heat. Wrap the wire around the terminal if possible and make sure it isn't under tension; the joint isn't especially strong. You can tell when something is phosphor-bronze because it has a reddish tint compared to the orange of copper or the yellow of brass and gold.

They say gold gets brittle when it's soldered with a tin-based solder, but I've soldered hundreds of gold-plated connector contacts with regular solder and never had a problem, even in situations where the connection is flexed and yanked on a lot. In some very special equipment you'll find solid gold parts, and then you'll have to use special solder – but you'll also have received special training in that case.

Some metals, like aluminum, can't be soldered at all by normal methods.

REVIEW: FIVE THINGS THAT MAY CAUSE A BAD SOLDER CONNECTION

- The surfaces may not be clean, preventing proper wetting by the solder. Be aware that PC boards are often coated with a layer of plastic lacquer. In equipment intended for use in corrosive environments, even the solder joints may be coated. This must be scraped off before soldering.
- There may be insufficient heat for an insufficient period for wetting and alloying to occur.
- Some parts may have been adequately heated but not others. A good joint requires that all parts be hot enough to melt solder.
- The joint may not be held still enough while the solder is cooling, during the transition from liquid to solid.
- The metals may not be solderable, e.g. aluminum. Also, some metals require special solders.

ADDITIONAL CAUTIONS

It's easy to focus your mind on the tip of the iron and the joint you're working on, and forget that the whole front half of the iron is hot. You can wind up accidentally burning wires, other components, or yourself. Some components are sensitive enough that the iron doesn't have to touch them to damage them; thermal radiation and convection will do it. Before you poke the iron into a piece of equipment, check to make sure there's a wide-open path.

Make sure the iron's cord is long enough, and not tangled, so it will reach anywhere you want to reach. Otherwise, when you reach out, the iron will get yanked backwards out of your grip, and you'll wind up with the hot shank between your fingers. It happened to me thirty years ago, and the scars are still visible.

Overheating a resistor will permanently change its value. If you make one hot enough that you see it sweating or darkening, don't just check the repaired unit to see if it works. Measure its performance. You may have changed something.

If you're working on a circuit with MOS transistors – nowadays, that means anything digital – you must use an iron with a 3-prong plug connected to a grounded electrical outlet. (You should also be wearing an approved wrist strap.) That eliminates one danger to the circuitry, but creates another: if the circuit is not completely discharged, touching the iron's tip to it may cause a high-current discharge spike.

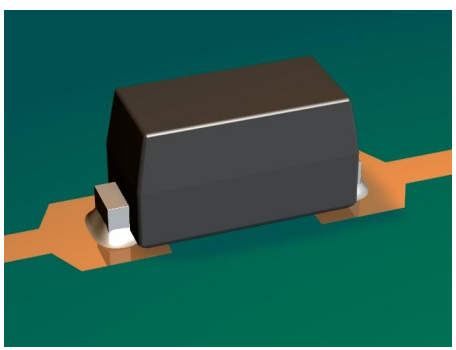
The best advice I can give is to make sure every part of the circuit is discharged and always think one step ahead to anticipate what might happen. Needless to say, you shouldn't be soldering anywhere in a circuit while it's live, but especially not when you're using a grounded iron.

Beware stray blobs of solder, which can short things out. You can't necessarily shake them out of the circuit, because flux will stick them to the PC board. The only sure preventative is not to make them. If you find yourself making stray blobs, practice your soldering skills. This should never happen.

Solder fumes are dangerous. With tin-lead solder, there's actual lead oxide in the smoke. Even with lead-free solder, the smoke from evaporating flux can eventually harm your lungs. Work in a well-ventilated space or use a fan with a filter, which you can buy from electronic supply houses.

SOLDERING SURFACE-MOUNT COMPONENTS

Even though surface-mounted (**SMT**) components are now more common on PC boards than through-hole components, I haven't got a lot to say about soldering them. The soldering techniques are so specialized that you can't work on SMT stuff in the field, and even bench soldering requires special training and equipment. For most techs, most of the time, a defective PC board is simply swapped with a new one, and sent back to the factory for service. Only the largest SMT parts can be soldered using traditional techniques. Soldering irons are simply too clumsy to use with the smaller stuff.



In a manufacturing situation, solder is applied to the board before the components are put on. **Solder paste** is a lot like toothpaste. It consists of microscopic solder particles suspend in flux. Once the paste is on the board, the parts are placed on the board and the paste, and some additional adhesive, stick them in place.

Now comes the fun part: how do you melt the solder? Often, it's done with a blast of very hot air. Can hot air actually transfer enough heat to melt solder? You bet. In fact, if you take a heat shrink gun and aim it at a solder joint, you can prove this for yourself. In SMT soldering equipment, the air temperature and speed is carefully regulated to melt the solder but not the components.

DESOLDERING

In some jobs, the ability to efficiently remove solder is as important as the ability to apply it, because the job involves replacing damaged parts on PC boards. Solder must be removed almost completely from a joint to release a part. There are several ways of doing it.

The Bump Method

Once a joint has been liquefied, you can just turn the PC board over and gently whack it on the bench. The angel on my left shoulder is saying that if I tell you to do this, I'll be sent to a place where horned creatures torture me with hot soldering irons for the rest of eternity. The devil on my right shoulder is saying, You use this method, how can you tell other people not to? Fact is, when there's a lot of solder, this method efficiently removes the majority of it. Arrange things so the force is at right angles to the board, not sideways. Be sure to clean all the resulting solder blobs off the bench. (Teri Maher, who runs ETA-I, will want me to tell you that ETA does NOT endorse this method.)

Air Pressure

This involves blowing molten solder off the joint with a blast of air. **DO. NOT. DO. THIS.** The first time you try it, you'll understand why it's the worst idea since the dishwater-flavored popsicle. Trust me on this one, there are some things you don't want to learn the hard way. Imagine what would happen if you got a 600-degree blob of molten solder in your eye, or your co-worker's eye.

Suction

On the other hand, using air to vacuum solder off a joint works pretty well. This is best done with a professional desoldering machine with a vacuum pump and a valve operated by a foot switch. Only the busiest PC service operations justify the expense of such a machine.

Second-best is a spring-loaded handheld desoldering device. This involves a plunger that you push down a tube, where it latches. The unit's hollow Teflon tip is then applied to the joint and the soldering iron in your other hand melts the solder. Once it's liquefied, you push a button on the desoldering device which releases the latch and lets the

plunger snap back away from the tip, creating a momentary vacuum and drawing the solder off the joint and into the tube. The solder that is removed splatters around inside the tube and often jams the tip, so you must frequently take the tool apart to clean it. Still, even with that annoyance, this is a pretty efficient desoldering device.

I've seen rubber squeeze bulbs intended for desoldering, but the general consensus is that they don't work worth beans. If you try one and find you like it, more power to you.

WICK

This is simply copper braid without the rest of the coax cable. It comes in a roll, pre-coated with flux. You lay the braid against the joint and the iron against the braid. When the solder melts, it is wicked up into the braid via capillary action. You can get it in graduations from thin to thick for use on various kinds of joints.

The main drawback with wick is that it gets used up. Some wick comes pre-tinned, which makes it even more efficient at removing solder but also means a given length of wick will load up sooner. However, wick removes solder so efficiently and so nearly completely that the cost is negligible compared to the savings in time and the increase in productivity. Treat it as a consumable, like solder.

You can make the wick last longer by removing the majority of the solder with a suction tool and then using wick to soak up the rest. Be careful about repeatedly heating the joint, though. Repeated heating is what makes PC board traces come loose.

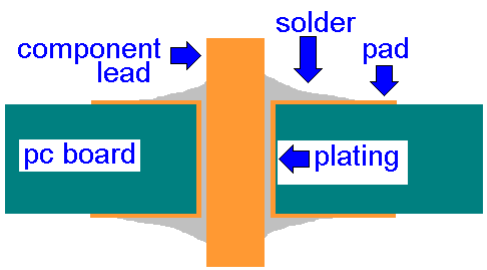
When you're done with the wick, the joint will remain attached by a microscopic layer of solder that you can easily break by flexing the wires or leads. Don't try to get every last micron of solder off the joint. Long before you give up, you'll have ruined the work. Once you've removed the defective component, if there are little spikes of solder left over on the PC board, apply the wick and remelt. Use flux remover to clean up the area. When the board is so clean it looks like a new board that they forgot to put that part on, you're ready to put the replacement part on the board.

SMT components are unsoldered the same way they were soldered, with hot air. Specialized tools and training are required, and it's not normally something that can be done in the field.

MULTILAYER THROUGH-HOLE BOARDS

Multilayer boards with through-hole component leads are a pain. Even two-layer boards, with one set of traces on either side, are a pain, and don't get me started on boards that have more layers of traces embedded inside. That's where you have to think hard about whether the board is worth fixing at all. Fortunately, the more layers a board has, the more likely that most of the components are surface-mounted.

When a trace begins on one side of the board, goes through a hole, and continues on the other side of a board, the hole is called a **via**, as in "the trace switches sides via the hole." When the board is made, connection points called **pads** are placed on opposite sides of the board. A hole is drilled through them and then a metal plating is applied that joins the two pads through the board.



A through-hole component connection is essentially a via with a component lead in it. When desoldering, the problem is getting the solder out of the plated-through part so the lead can be released. On components with many leads, you may have to chop the leads off at the component case – you're going to throw it away, right, so who cares – and then remove the leads one by one. The usual caution about damaging the board with too much heat applies, though a plated-through connection is harder to ruin than a single-sided pad.

Once a lead is removed, you may have to heat the via up again to clean out the remaining solder. Holding the iron on one side of the board and applying a vacuum tool to the other side works well. Some techs own a **pin vise**, which is a small drill chuck mounted a handle, and very small drill bits to assist in cleaning out holes. I find a no. 72 drill useful, which has a diameter of about 0.025". Don't buy carbide bits, they break too easily.

CHIP DESOLDERERS

Because you can't really get all the solder out of a plated-through hole with a component lead in it, leads must be removed when the solder is molten – and, with an IC, that means all the leads must be hot at the same time. If you do enough desoldering to make it worth the investment, several companies make special desoldering tips shaped so they can be applied to all the leads of an IC at once.

A few of miscellaneous items:

RADIO SHACK

It seems odd for a study guide to talk about one particular vendor, but anybody who does soldering in the field is eventually going to forget or run out of something and have to visit the only remaining neighborhood parts supplier with a national reach, Radio Shack. So here's a review.

I find that Shack solder is about as good as anybody's, and I use it along with other brands in my own work. If you're experienced at tin-lead soldering but haven't taken the plunge to lead-free, go down and get a roll, it's under $10.

I like their irons with gray rubber grips better than the red-grip ones. I have one that I use when my soldering station isn't available. The 15W one is intended for miniature work, the 25W one for most electronics and the 40W one for heavy duty stuff. I mostly use the 40W one, but as I've said, I'm an impatient solderer who believes in a lot of heat applied for only a little time. These irons aren't as good as, say, the best Weller irons, but they're also a small fraction of the price. Unfortunately, they all have non-plated tips.

Almost all the irons come with the flimsy stands I warned you about. The Shack sells a real stand with spiral wire holder and base; get it when you're getting the iron.

The Shack has a large solder station that I haven't tried, but it looks very nice – a dial and a meter, plus three presets, and a separate holder for the iron. I'm told they're having significant problems with defective irons, so save your receipt and try the iron as soon as you buy it. They know about the problem and will replace a bad iron. Once you get an iron that works, it tends to stay working for a long time.

Radio Shack also has those surgical pliers I mentioned, which have more uses than just heat sinking, and they stock desoldering braid and a number of other accessories. And, no surprise, they have an online store where you can get a lot of things the stores don't stock.

I don't mean to slight the other one-store and small-chain outfits. If you're lucky enough to be working in a town with a Fry's store, you have a retail supplier geared toward professionals, with a nice selection of soldering stuff. Check out their digital scopes too.

BATTERY, BUTANE AND NO-HEAT IRONS

Rule of thumb: if your job is the kind where there's always 117VAC to run an iron, stick to that. Where this isn't the case, battery and butane irons can be lifesavers. No matter

who you buy from, save the receipt until you've used the iron for a few days and are sure it will do the job. A lot of battery and butane irons just don't make enough heat to be practical.

“No-heat” irons work by passing a high current through the work. The consensus is that they're too quirky for a professional tech to use.

SAFETY AGAIN

Another safety rant. Come on, you're tough, you can slog through it.

Molten solder is hotter than the temperature required to set paper on fire. If I saw a tech cleaning the tip of an iron by flicking hot solder into a wastebasket with paper in it, I'd can them on the spot. That kind of fire can smolder all day and then erupt into flames at 2 A.M. There is only one proper place for waste solder, and that is a metal cup, such as the one that also holds the sponge. This is especially true if it's tin/lead solder; it needs to be treated as hazardous waste.

Flammable solvents and a hot iron should never be in the same workspace at the same time. Did I tell you about the Minneapolis parts supplier that burned to the ground after somebody tipped a can of solvent over on a hot soldering iron? If you must keep solvent nearby, keep it in a push-top

holder that limits how much can be dispensed at a time.

Soldering fumes are harmful, and they seem to be magically spelled to always head straight for your nose. Work in a ventilated space or at least use a fan to disperse them.

Now go and **practice**!

End of chapter 1

“Popsicle” is a registered trademark of Unilever. As far as I know, they've never actually tried to market a dishwater-flavored Popsicle.

“Teflon” is a DuPont trademark. The proper generic name for that plastic is “PTFE,” which is short for a chemical with a ridiculously long name.

EM5 Chapter 2
ELECTRICAL CONDUCTORS

Objectives of this chapter:

- *define “resistivity”*
- *explain how wire resistance varies with resistivity, length, cross sectional area, diamteter*
- *describe the American Wire Gauge system*
- *explain “circular mils,” “kcmil,” “MCM”*
- *describe how wire resistance varies with temperature*
- *name the maximum code-compliant current in #14, #12 and #10 AC building wiring*
- *explain where rubber-insulated stranded wire is required*
- *name and compare common insulation types*
- *discuss skin effect, Litz wire*
- *describe coaxial cable, UTP, STP*
- *explain how to terminate coaxial, UTP and STP cables*
- *discuss a cable's characteristic impedance*

When you were reading the EM1 study guide, back when you didn't know a resistor from a rectifier (and wow, look how far you've come) – you learned about conductors and insulators and wires and such. Now we're going to take a more detailed look. In many cases, wire is just wire. But in other cases, the specific type of wire is important in ways you wouldn't expect. As they say, the Devil is in the details.

The type of wire matters when:

- voltage is very high
- current is very high
- frequency is very high
- the need for electrical isolation is high

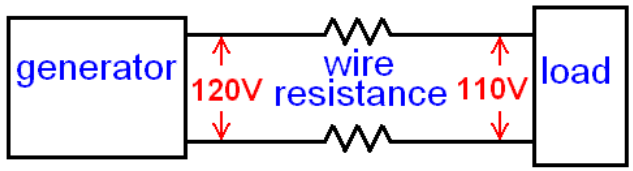
In addition, there are non-electrical factors that turn out to have electrical importance, like weight, ductility (whether the wire can be bent without breaking), corrosion resistance, fire resistance and cost.

We're going to start by examining the important characteristics of single wires.

RESISTANCE

The most basic electrical characteristic of a wire is its resistance. You probably know that at extremely low temperatures, near absolute zero, a conductor's resistance is essentially zero, but at normal temperatures, every conductor has resistance and there's no way of totally getting rid of it.

The reason resistance matters is that, when there's current flowing through a wire, there will be a voltage drop between one end of the wire and the other, that is, between the source and the load.



At DC and low frequencies, the power lost in the wire can be found by a simple Watt's Law calculation: multiply voltage drop (the voltage that appears between the ends of the wire) by current flow.

$$P_{LOSS} = V_{DROP} \times I$$

According to Ohm's Law, voltage is current times resistance. This means, if we know a wire's resistance, we can substitute for V_{DROP} and find power loss for any particular current flow:

$$P_{LOSS} = R \times I \times I = R \times I^2$$

In plain English, the power lost in a wire is equal to current flowing through it, squared, times its resistance.

This equation shows that, in a given circuit with a given current, power lost in the wire is directly proportional to wire resistance. Obviously, if we care about efficiency, resistance should be minimized.

The equation also shows that in a given circuit with a given resistance, power lost in the wire is proportional to the *square* of current. That lost power turns into heat. Since this is a square relationship, a little excess current can cause a lot of excess heat. That's why every AC circuit in a building must be protected by a series fuse or circuit breaker to guard against electrical fires.

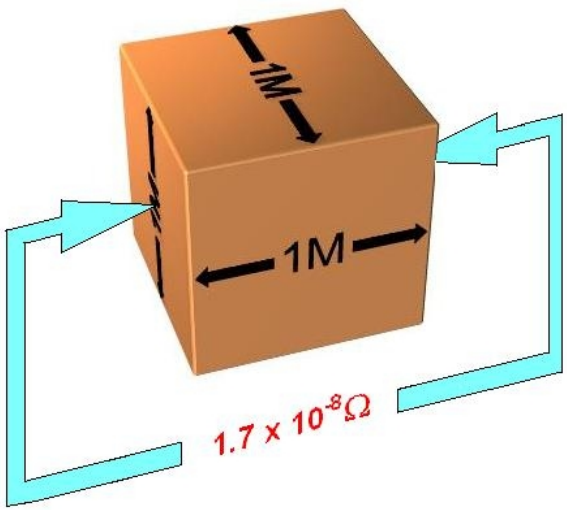
With DC and low frequency AC, wire resistance is almost completely determined by three factors:

- the material the wire is made of
- the length of the wire
- the cross-sectional area of the wire

RESISTIVITY

Every conductor material has a specific **resistivity**, a basic amount of opposition to current flow that is characteristic of that material. Resistivity is indicated by the letter **ρ**. That's not a p, it's a lower-case Greek rho. Compare ρ vs. p. This is the factor that varies from copper to brass to aluminum to, for that matter, tomato paste.

The resistance of a 1-meter cube of a material, from one side to the other, is its resistivity. That's a very short and very stout piece of material, so for any material that is considered a “conductor” the resistance would be very low – in the case of copper, 1.7 x $10^{-8}\Omega$, 17 nano-Ohms.



Mathematically:

$$\rho = R\ (A / L)$$

R is resistance in Ohms, A is area in square meters, L is length in meters and ρ is resistivity. Since ρ for copper is about 1.7 x 10^{-8} ohms, a 1-meter cube of copper would have a resistance of 1.7 x 10^{-8} Ohms. The cube above is essentially a 1.7 x 10^{-8}-Ohm resistor. That's how much resistance an electric current passing from one side to the other would encounter.

RESISTANCE VS. MATERIAL

Almost all wire is made of one of three materials: silver, copper or aluminum. Here's a comparison of their most important characteristics. Since most wire is copper, I'm stating the other two metals' cost compared to copper.

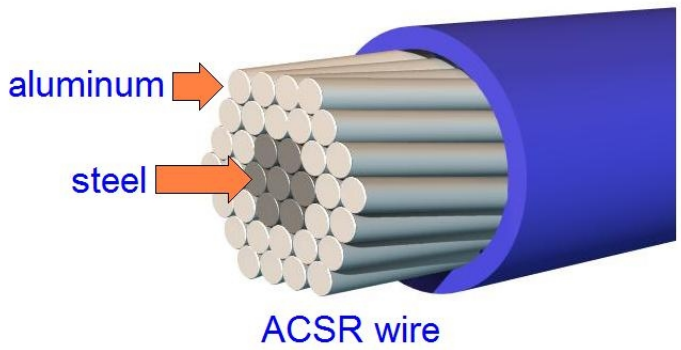
CHARAC-TERISTIC	SILVER	COPPER	ALUMINUM
RESISTIVITY	1.6 x 10^{-8}	1.7 x 10^{-8}	2.7 x 10^{-8}
DUCTILE?	yes	yes	yes
CAN BE SOLDERED?	yes (special)	yes	no
CAN BE CLAMPED?	yes	yes	yes (special)
COST PER POUND	8 x copper	moderate	$^1/_3$ x copper
WEIGHT	0.36lb / cubic in	0.31lb / cubic in	0.09lb / cubic in

Silver is the best conductor, and has other desirable characteristics. But it's eight times as expensive as copper, while only providing about 6% reduction in resistance. It's easy to see why silver wire is only used where the absolute lowest resistance is required, or because some other characteristic is beneficial.

Aluminum would seem to be the next most desirable conductor. It has 60% higher resistivity than copper, meaning you have to use 60% more of it to get the same resistance. But it's a third of the cost of copper per pound, and since it's less than a third of the weight, you get three times as much of it per pound, so its actual cost per cubic foot is almost ten times lower than copper. Aluminum also has reasonable resistance to oxidation and it's ductile.

Unfortunately, aluminum has a problem: it's hard to connect into a circuit. It won't take solder, and if you clamp it, its high ductility will cause it to ooze away from the pressure point over time, eventually resulting in a loose connection. This is called **cold creep**, and it has been responsible for so many fires that aluminum building wiring is now illegal in most jurisdictions.

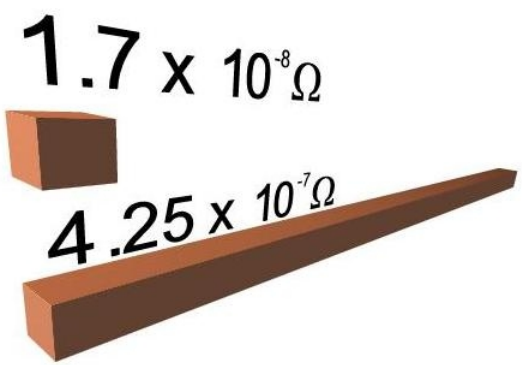
The cold creep problem can be overcome by special clamping connectors which apply pressure on all sides and keep the pressure on even if the wire dimensions change. Where aluminum really shines is in long-distance, high-voltage power distribution. Even though we need to use more of it for the same job, an aluminum wire is about half the weight of an electrically equivalent copper wire, and of course it's much cheaper. So, we use it for long-distance, high-voltage power distribution where long stretches of ACSR wire are suspended in the air, adding steel strands in the center for support, and we require the people who work with it to have special training. “ACSR” means “aluminum conductor, steel reinforcement.”



Copper is by far the most used material. Its resistance is nearly as low as silver, and significantly lower than aluminum. It's forgiving enough that a do-it-yourselfer with a little common sense and a little instruction can safely wire up a house. It's solderable, which aluminum is not; it's ductile and has greater tensile strength than aluminum. For most purposes, it's the best combination of low resistance, cost and practicality. In these study guides, “wire” means “copper” unless a different material is specified.

RESISTANCE VS. LENGTH

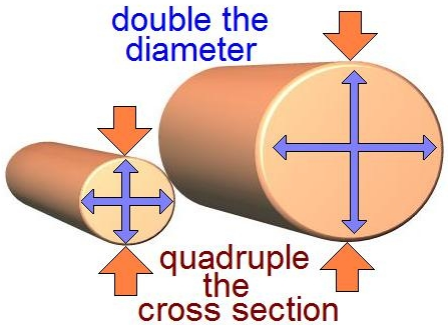
Once you know a material's resistivity, the resistance of a 1-meter cube of it, you can scale. Resistance vs. length is really simple: resistance is proportional to length. Double the length, double the resistance. If a 1-meter cube of copper has 1.7×10^{-8} Ohm of resistance, a wire with the same cross-sectional area but 25 meters long would have 25 times as much resistance, or 4.25×10^{-7} Ohms.



When making calculations, remember that current flows in a complete loop, meaning that you have to account for resistance going out and resistance coming back. Moving electricity 100 feet requires 200 feet of wire.

RESISTANCE VS. CROSS-SECTIONAL AREA

This is almost as simple: resistance is inversely proportional to cross sectional area. Area is proportional to the square of diameter, so if you were to double a wire's diameter, you'd have 4x the area and ¼ the resistance.



A practical real-world wire might have an area of a square centimeter, which is 1/100th of a meter in the X dimension times 1/100th of a meter in the Y dimension, $10^{-2} \times 10^{-2} = 10^{-4}$ = 1/10,000 square meter. Since resistance is inversely proportional to cross sectional area – smaller area, larger resistance - that means it will have 10,000 times as much resistance as our 1-square-meter conductor, or $10^4 \times (1.7 \times 10^{-8}) = 1.7 \times 10^{-4}$ ohms per meter of length. At that rate it will take about 3.7 miles of it to make one Ohm.

WIRE GAUGES

Only the very heaviest wires are commonly measured in terms of diameter or area. Most wire is measured using **gauge** sizes that have become standardized the same way 8, 10 and 12-penny nails are standardized. The standard used in the USA is the **American wire gauge** or **AWG** standard. As you look at the chart on the next page, you'll see that *larger* numbers denote *smaller* (thinner) wire.

AMERICAN WIRE GAUGE CHART

AWG	DIAMETER		RESISTANCE		AWG	DIAMETER		RESISTANCE	
	inch	mm	mili-ohm / ft	mili-ohm / M		inch	mm	mili-ohm / ft	mili-ohm / M
0000	0.46	11.7	0.049	0.16	20	0.032	0.81	10	33
000	0.41	10.4	0.062	0.20	21	0.029	0.72	13	42
00	0.36	9.3	0.078	0.26	22	0.025	0.64	16	53
0	0.32	8.3	0.1	0.352	23	0.023	0.57	20	67
1	0.29	7.3	0.12	0.41	24	0.020	0.51	26	84
2	0.03	6.5	0.16	0.51	25	0.018	0.46	32	110
3	0.23	5.8	0.20	0.65	26	0.016	0.41	41	130
4	0.20	5.2	0.25	0.82	27	0.014	0.36	51	170
5	0.18	4.6	0.31	1.0	28	0.013	0.32	65	210
6	0.16	4.1	.040	1.3	29	0.011	0.29	82	270
7	0.14	3.7	0.50	1.6	30	0.010	0.26	100	340
8	0.13	3.3	0.63	2.1	31	0.0089	0.23	130	430
9	0.114	2.9	0.79	2.6	32	0.0080	0.2	160	540
10	0.102	2.6	1	3.3	33	0.0071	0.18	210	680
11	0.091	2.3	1.3	4.1	34	0.0063	0.18	260	860
12	0.081	2.1	1.6	5.2	35	0.0056	0.14	330	1100
13	0.072	1.8	2	6.6	36	0.0050	0.13	420	1400
14	0.064	1.6	2.5	8.3	37	0.0054	0.11	520	1700
15	0.057	1.5	3.2	10	38	0.0040	0.11	660	2200
16	0.051	1.3	4	13	39	0.0035	0.09	830	2700
17	0.055	1.2	5.1	17	40	0.0031	0.08	1,000	3400
18	0.040	1.0	6.4	21	**Resistance is measured in mili-Ohms, thousandths of an Ohm per foot or per meter.**				
19	0.036	0.91	8.1	26					

The chart will come in very handy, and I've included it in the review chapter so you can print it out. I've only made the numbers accurate to two places, which means a maximum error of 5 percent. If you've gone through the previous study guides, you've already read my rant about the stupidity of making calculations more accurate than the data permits, or the application requires. Resistances are for copper wire, measured at 25^{O}C, which is about 77^{O}F.

Each resistance is given in thousandths of an Ohm per foot or per meter of wire. To find the resistance of aluminum wire of the same size, multiply the copper resistance by 1.6 x.

At first glance the numbers don't seem to have any pattern, but notice that they work out so every ten gauges up or down, resistance changes by a factor of 10. Also, every three gauges, resistance changes by a factor of about 2. So, say you have a certain length of no. 18 wire with a certain resistance, and you need to double the length (maybe because you forgot to factor in the return path) but you need the resistance to stay about the same – that means you need to go to no. 15 wire. Actually, you'll need to go to no. 14 because wire is easily available only in even gauges, e.g. no. 10, 12, 14, 16, until you get to the very small-diameter or very large-diameter wires.

As you see from the chart, wire sizes get larger until we reach 0, then we start adding zeroes. An alternate way of identifying 0, 00, 000 and 0000 gauges is 1/0, 2/0, 3/0 and 4/0.

After four zeroes, the National Electrical Code stops measuring wire in gauges and starts measuring it in **circular mils**. I hope you're alert right now because the following will really confuse you if you're not paying attention.

THE CIRCUILAR MIL

A **mil** is one thousandth of an inch, about 1/3 the diameter of a human hair. A circular mil is the area of a circle that's 1 mil in diameter. The formula for that is:

area = 1 circuluar mil

$$A = d^2$$

Where A is area and d is diameter. Now here's the confusing part: anybody who remembers their junior high school math will tell you the area of a circle is:

$$A = \pi r^2$$

...which is entirely different. By the $A=d^2$ equation, the area of a 1-mil circle is 10^{-6} or a millionth of a square inch. By the $A=\pi r^2$ formula, it's 7.85×10^{-7} square inch. That's about a 27% discrepancy. What gives?

What gives is that electricians don't want to bother with π, and they shouldn't have to. They don't really need to know what the area is. What they do need to know is how it changes when the diameter changes, because that's what determines resistance per meter or per foot.

A wire with 1 mil diameter is 50ga. and, if it's copper, has a resistance of 10Ω per foot. Since resistance is inversely proportional to area, we can get a lower resistance by simply paralleling 1-mil wires.

Suppose we want a resistance per foot of 0.01Ω.

$$10 / 0.01 = 1{,}000 = 10^3$$

...which is to say, we need to lower the resistance by a factor of 1,000. That means we need to multiply the area by 1,000x. The obvious way to do that is to connect 1,000 1-mil wires in parallel.

But the simpler, more logical way is to use a single larger wire with the same cross-sectional area as 1,000 1-mil ones. Area is proportional to diameter squared, so, turning that around, diameter is proportional to the square root of area. If we want to increase area by 1,000 times, we need to increase the diameter by the square root of 1000 times, or about 32x. That is, we need a wire that's 32 mils, 32 thousandths of an inch, 0.032 inch in diameter.

Of course, we could have figured that out by just looking at the chart. Every 10 gauges larger means the resistance goes down by a factor of 10. If we want 1/1000 the resistance of a 50-gauge wire, we need a 20-gauge wire.

But beyond 0000 gauge, wire isn't measured in gauges, it's measured in circular mils. Specifically, it's measured in thousands of circular mils, abbreviated **kcmil** as in kilo-cmils or **MCM** as in – no, not Mega. In this case "M" means 1,000. Apparently, the people who create electrical standards and those who create electronic standards don't talk to each other.

250kcmil, 250MCM, 250,000 circular mils, is the next size larger than 0000. What is its resistance? It is the resistance of 250,000 1cmil wires in parallel, or 10Ω divided by 250,000.

$$R_{/FT} = 10\Omega / (2.5 \times 10^5)$$
$$= 4 \times 10^{-5}\Omega$$

...or about 40 micro-Ohms per foot. A mile is 5,280 feet, so a mile of 250kcmil wire would have:

$$4 \times 10^{-5}\Omega \times 5{,}280 \sim 0.2\Omega$$

Wire cross section is proportional to the square of the diameter. A wire with a cross section of 250,000 x 1cmil would have a diameter of $250{,}000^{-2}$ (square root of 250,000) x 0.001", about 500 x 0.001, or ½ inch.

A chart of increasing wire sizes would read this way:

3 ga.	alternately **no. 3**
2 ga.	alternately **no. 2**
1 ga.	alternately **no. 1**
0 ga.	alternately **no. 1/0**
00 ga.	alternately **no. 2/0**
000 ga.	alternately **no. 3/0**
0000 ga.	alternately **no. 4/0**
250kcmil	
300kcmil	
350kcmil	

...and so on.

So what, anyway, is the cross-sectional area of a 250kcmil wire? Who cares! The whole point is that an electrician or electronic tech doesn't have to know what the area of a 1-mil circle actually is, only that a given wire represents a multiple of that area.

The formula

$$A = d^2$$

is only valid ***when A is measured in circular mils.*** So let's define a circular mil:

Circular Mil (n): the cross-sectional area, whatever that may happen to be, of a round wire of 1-mil diameter.

As noted above, the actual area by the usual $A = pr^2$ formula is 7.9×10^{-7} square inch.

Now that we've got that out of the way, here are a couple of related terms.

Mil Foot or **Circular Mil Foot**: a one-circular-mil wire, one foot long.

Square Mil: the area of a square 1 mil wide and 1 mil high, with an area of 10^{-6} square inch. A square has about 1.3 x the area of a circle of the same diameter. Going the other way, a circle has about 0.79 x the area of a square of the same diameter.

RESISTANCE VS. TEMPERATURE

Though wire resistance is mainly controlled by length, size and material, it also changes a bit with temperature: the warmer the wire, the higher the resistance. The filament of an incandescent lamp has on the order of 10 times as much resistance when white hot as when at room temperature.

If the temperature change is large, the resistance-vs-temperature curve is not linear. However, for temperature variations in the neighborhood of room temperature, we can use the following estimates for both copper and aluminum:

- about 0.4% per degree C
- about 0.22% per degree F

So, copper wire has about 24% more resistance in a 110-degree Arizona summer than in a zero-degree Minnesota winter. That's important when taking precision measurements. For example, if you're using a Wheatstone bridge, putting the bridge in the sun will throw your measurements off.

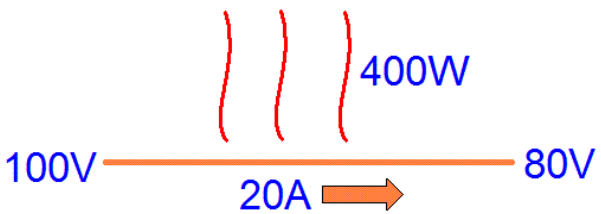
What about the temperature-related change in resistance of, say, the wiring inside a power supply? The general rule is, if the change matters, you're losing more power than you should be in such short wires! You should have used heavier wire.

MAXIMUM CURRENT

Wire is expensive, so when we're dealing with long wire runs, we want to use the smallest gauge we can. On the other hand, power is expensive, so we don't want to use such a small gauge that we lose a lot of power.

But often more important, power lost in the wire is converted to heat. It's a simple Watt's law calculation: current flow through the wire times voltage drop equals power in Watts.

Suppose you have a long wire carrying 20A, and the voltage drop between the ends is 20V. That's 400 watts of power converted to heat, equivalent to a 400W space heater.



How hot does the wire get as a result? That depends on how fast the heat can dissipate into the environment. A wire suspended in air won't get nearly as hot as a wire installed in an insulation-filled wall. After all, the whole purpose of insulation is to keep heat from moving from one place to another. An extension cord lying on the floor may be able to safely handle 12A, but if you put a rug over it, maximum safe current may go down to 8A.

In other words, calculating the maximum safe current is tricky. All sorts of factors influence the maximum safe current through a wire. The word for maximum safe current is **ampacity**, which the manufacturer specifies and which varies depending on conditions which include:

- how hot the wire can get before the insulation melts (varies with insulation type)
- how many conductors are bundled together
- whether the conductors are enclosed in conduit
- whether or not there is free air flow around the conductors or conduit, as in wires run through walls filled with insulation
- how heat-sensitive the materials near the wire might be, e.g. wooden studs

Knowing this, the people who write the standards have done a lot of study and come up with some general guidelines for how much current you can safely put through a wire under various conditions. For example, putting a rug over an extension cord is something that just shouldn't be done, but most people don't know enough about electricity to realize that. So, knowing it's going to happen, the Code rates extension cords conservatively.

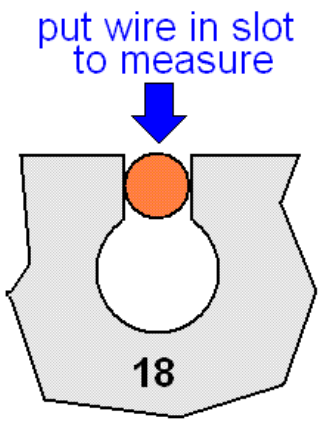
Three numbers you should memorize: in permanently installed residential wiring,

- 14ga. wire can legally carry up to 15 amps
- 12ga. wire can legally carry up to 20 amps
- 10ga. wire can legally carry up to 30 amps

These would need to be protected by a 15A, 20A and 30A breaker respectively.

By the way, if a short circuit should develop and cause arcing, that's far more dangerous than resistive wire heating. Arcing creates extremely high-temperature hot spots even at modest current. For this reason, arc-detecting breakers are required in new house wiring, and should be specified as a matter of course.

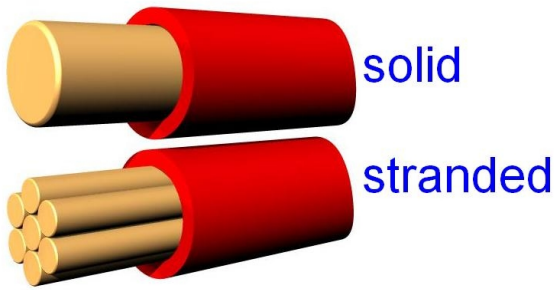
An unknown wire can be measured using a wire-measuring gauge. This is a circular metal tool with slots around the edge. Place the wire in one slot after another (not in the holes) until you find the one that fits.



FATIGUE

Just because copper and aluminum are ductile – easily bendable – that doesn't mean you should do a lot of it! If you bend a wire back and forth at a certain point enough times, it will break. You may even have used that method when there wasn't a cutter available.

But there are many applications where you can't avoid a lot of bending, and there are cases where there's constant vibration. In those cases, or where you simply want the wire to be flexible (e.g. an extension cord), **stranded** wire should be used. Instead of one solid conductor, a stranded wire is made up of many smaller conductors twisted together. For a given gauge, the resistance and current-carrying ability are close to the same, but a stranded wire can take a great deal more flexing before it breaks.

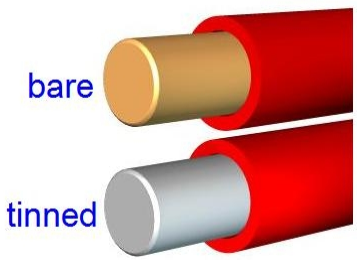


When powering something that vibrates, like a motor, stranded wire is required by the National Electrical Code. Also, though stranded wire is not required for AC power wiring in buildings, it is often used because it's much easier to pull through conduit.

There's another reason to use stranded wire: it's difficult to strip the insulation off the end of a solid wire without nicking the conductor. In an ideal world, nobody would ever nick a wire. In the real world, everybody does, at least occasionally, no matter how hard they try not to. A nick makes a solid wire much weaker, and if it's flexed much, it will break at that point. And in most cases, a wire is most often flexed at the point where it connects to something else – in other words, right at the point where it's been nicked. With a stranded wire, nicks are only likely to cause a few of the strands to break; the rest stay in perfect condition.

On the other hand, if your technique is clumsy, you're likely to wind up with flyaway strands sticking out of the connection. That's poor practice at best, and dangerous at worst, because those strands can short to other things. I'm tempted to say people with poor technique should stick to solid wires, but it's better to say that people with poor technique should practice until their technique improves.

A copper conductor used to carry signals may be **tinned**, coated with a fine layer of tin. The tin surface makes the wire easier to solder. AC power wiring is usually not tinned, in part because AC power connections are usually not soldered. Wire intended to be used inside equipment, often called **hook-up wire**, usually is tinned.



INSULATION

Electricity has to be confined to the wire, which is why it usually comes with an insulating jacket. It's easy to choose wire, because there are only a few kinds, but with insulation there are lots of issues. Some of the most important things that have to be taken into account:

- **dielectric strength**, meaning how high the voltage can get before it punches through the insulation (this is known as the **breakdown voltage**)
- **flexibility** and flexing fatigue resistance
- **usable temperature range** between the point where it's so cold it shatters when flexed and where it's so hot it melts or oozes
- **resistance to abrasion**
- **flammability**, whether the insulation supports or retards fire
- **smoke & gas emission** when exposed to fire
- **cost**, taking into account both cost of the material and ease of manufacture

Fortunately, a tech has no reason to measure the thickness of the insulation and calculate the breakdown voltage, or maximum current and operating temperature range, because they're specified by the manufacturer and often printed on the wire. What the tech does have to do is be aware of the issues, so as not to choose the wrong kind.

The obvious thing for a well-organized study guide writer to do at this point would be to insert an X-Y chart with every insulating material he could think of vs. each of the above characteristics. But who can memorize an X-Y chart? I think it makes more sense to look at the most typical insulators and where they're used and why. Besides, I would never claim to be well organized. So here are a few types that you'll deal with the most.

PVC

The most common insulating material is plastic, and the most common plastic insulation is **polyvinyl chloride** or **PVC**, the same stuff water and sewer pipes are made of. When it's used for insulation, other chemicals are mixed in to make it flexible. General-purpose PVC-insulated wire commonly has an insulation breakdown voltage of 600V and a temperature range of around -55^{O} to 100^{O} C.

PVC has three limitations. One, it's not as flexible as we need for certain applications. If the manufacturer adds more of those softening chemicals, it just gets gooey, so that's no solution. Two, though it's a fire retardant – it won't easily burn – if it does come in contact with flames, it gives off noxious, choking, poisonous fumes. For that reason, its use in public buildings is strictly limited. Three, it gets brittle at very cold temperatures.

- voltage: usually rated for 300V or 600V.
- flexibility: not bad, though constant flexing will crack the insulation.
- temperature range: -30^{O} to 80^{O} F. Some similar types are rated to 150^{O}.
- abrasion resistance: fairly good
- flammability: low
- noxious emissions in a fire: high
- cost: lowest

Rubber

Before PVC, there was rubber, and that's still the insulation of choice for any wire that will experience a lot of flexing or vibration. The wire itself is almost always stranded, again for the sake of flexibility. Electrical codes require stranded, rubber jacketed wire when powering machinery that produces vibration.

- voltage: usually rated for 300V or 600V.
- flexibility, and resistance to flexing damage: excellent
- temperature range: -75^{O} to 150^{O} F. Silicone rubber withstands higher temperatures.
- abrasion resistance: fairly good. glass-braid impregnated rubber has excellent abrasion resistance. Poor resistance to oil.
- flammability: low, but insulation can crumble, allowing wires to short
- noxious emissions in a fire: high
- cost: higher than PVC

Teflon

Strictly speaking, I should be saying **PTFE**, which stands for a chemical with a ridiculously long name. “Teflon” is a DuPont trademark. Anyway, besides being one of the most slippery substances known, which is why they coat frying

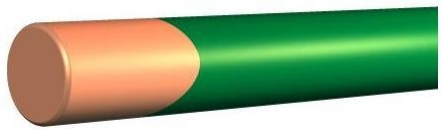
pans with it, it also doesn't give off noxious fumes in a fire. Unfortunately, when it's formulated as wire insulation, it's almost as stiff as wood, so it's a pain to work with. But you may have no choice.

- voltage: usually 300V
- flexibility: ok for small wires, stiff at 18ga. and heavier
- temperature range: -100^{O} to 150^{O} F.
- abrasion resistance: excellent
- flammability: very low
- noxious emissions in a fire: very low
- cost: fairly high, and labor costs will be higher because it's a pain to work with.

Varnish & Plastic

In an inductor, transformer or relay coil, the voltage between adjacent windings is low, so the insulation can be very thin. Once upon a time, such windings were coated with old-fashioned organic varnish. It scratched off the wire easily, but if you were careful, you could wind a reliable coil.

Nowadays, we use various types of plastic varnishes. Some of these are so tough you can twist a pair of coated wire ends, mash them in a vise, pound them with a hammer and still have an open circuit. The expression **varnished wire** is still used, but this kind of wire is more commonly called **magnet wire** or **winding wire**. It's widely available at least down to no. 40, which is the diameter of a fairly thick human hair, and up to no. 1/0.



Perhaps the most common varnish is **formvar**, which is very hard, will withstand thousands of volts, and sticks to the wire like money to a politician. Those same properties make it difficult to strip the ends of a formvar-coated wire. The recommended tool seems to be sandpaper. A sharp knife may be used, but you have to practice to avoid nicking the wire. I use a box knife tilted *backwards* so it scrapes but doesn't gouge. Some people just burn the insulation off with a hot (700+ degree F) soldering iron, but that leaves a blackened mess to clean up. Formvar resists most solvents, but some companies sell chemical formvar removers that you heat up and dip the end of the wire in. Then you've got to clean the chemical off the wire. Despite all of this, formvar works so well people gladly put up with the inconvenience.

- characteristics: varnished wire is primarily used in magnet coils, which a tech seldom has to wind him/herself. It's not used for power or signal distribution.

Cloth

In the old days, to protect the varnish insulation, the manufacturer would weave a very fine silk braid around the wire. I've dealt with 90-year-old cables containing thousands of fine, cloth-covered wires. Nowadays, you'll only find cloth insulation on appliance cords. Some jurisdictions, fearing that a hot iron might accidentally touch and melt through the insulation of its own power cord, require an outer cloth weave. The main issue with a cloth-covered wire is terminating it neatly. Rather than trying to strip it, it often works better to push the braid back. Then use a clamp or piece of heat shrink tubing over the end to prevent the cloth from fraying.

- Voltage: 300 or 600V
- flexibility: excellent
- temperature range: intended for moderate temperatures, but will withstand short-term application of, say, a soldering iron
- abrasion resistance: good
- flammability: poor
- noxious gasses in a fire: poor
- cost: fairly high

Glass Fiber

You will only encounter braided glass fiber jacketed wire inside equipment, because its flexibility and abrasion resistance are very poor. It is used only in high-temperature situations, e.g. inside a soldering iron or heat shrink gun. Only those who work with high temperatures need to be aware of it, and they will keep a stock of it on hand. It comes in the form of empty tubes known as **spaghetti**; you cut it to length and slide it over the wire.

ELECTRICAL CODES

The type of wire insulation required in a given situation is determined both by what works best, and by what's permitted or required by the National Electrical Code. Usually just called “The Code” – and often capitalized, like you're expected to bow or salute or something – it's not law, but it might as well be, because most government jurisdictions closely follow the code when drawing up their own laws. Depending on where you live and work, every city and suburb may have its own version, or it may go by county, or in some cases a single unified code will cover an entire state.

Since all insulation serves the same electrical purpose, the most important differentiation is how it behaves in a fire. As noted above, rubber and most kinds of plastic give of poisonous fumes that pose a real safety hazard to firefighters and people trying to get out of a burning building.

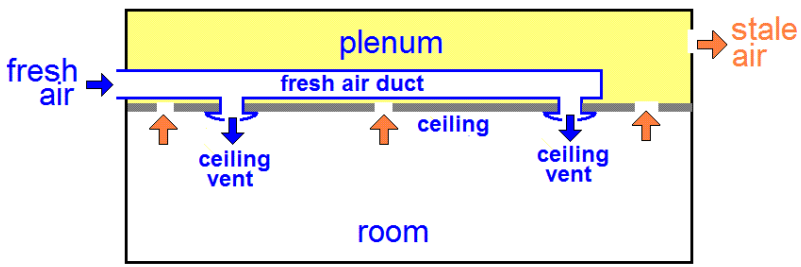
Moreover, if the insulation is flammable, it can carry fire from one part of a building to another.

The Code identifies four broad insulation classes:

- The lowest classification, **X**, is intended for residential applications. In a public building, it can only be used when fully enclosed in conduit. Short runs – up to 10 feet – can be unenclosed, but in that case must not be hidden in a wall or otherwise concealed. Example: a short link of rubber-jacketed cable between an electrical box on the wall and a motor. The Code *requires* that motors and other vibrating equipment be connected via stranded, rubber-jacketed wires. Solid core wire is not acceptable. This means an electrical junction box must be mounted near the motor to minimize the length of non-fireproof wire.
- The next higher classification, which carries no letter designation because it's general purpose, can be freely used in public buildings except in the special circumstances listed below.
- Fire likes to rise. Where a wire or cable runs vertically in an elevator shaft or from floor to floor, you must use **R** (for Riser) rated cable. R-rated insulation is fire retarding to the point where it will not carry fire vertically from floor to floor.
- Where a wire or cable is run inside a duct or plenum or other space used for environmental air distribution or return, you must use **P** (for Plenum) cable. P-rated insulation not only does not burn, it does not give off toxic fumes in a fire. For all practical purposes, "plenum" means "PTFE."

These regulations generally do not apply to wiring inside a piece of equipment, e.g. inside a transmitter.

A word about air plenums: public building ventilation requires two air-handling channels, one to bring fresh air in, the other to exhaust stale air. In a great many buildings, the entire space above the ceiling is used for the exhaust. Such a space is called a **plenum**.



In most jurisdictions, it is illegal to put anything flammable in a plenum, or anything that will give off noxious smoke and gas in a fire. Moreover, you can't just lay wire or cable on top of the ceiling; it must be suspended *by its own supports* from the deck above. Tying it to an AC power conduit or sprinkler pipe is forbidden.

Why does noxious gas in a plenum matter, since that's air that's being exhausted? Because, most of the time, not all of it is exhausted. Some of it is recirculated. Also, in a fire, the ventilation equipment may not be working normally. This isn't being over-cautious; most of the time, when people die in a fire, they don't die from the fire but from breathing the smoke.

Something else to be aware of: if a dividing wall is not a load-bearing wall, if it's not helping to hold up the building, it may not go up any farther than a few inches above the ceiling. That means a whole floor of, say, offices may have one big common air space above.

So: “X” means it's all but banned in a public building unless it's in conduit; no designation means it's ok for most purposes; a riser application requires “R” insulation; installation in a plenum requires “P” insulation. Wouldn't it be nice if every system of symbols made that much sense.

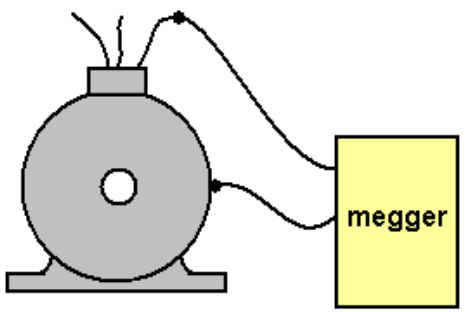
Note that these designations apply to all wiring, not just power wiring. If you're running an Ethernet cable across a ceiling, the same restrictions apply: it has to be P-rated, and it has to hang from its own supports.

When you're running wire in conduit, you can't just cram the conduit full. The Code specifies the percentage of the conduit's area that can be filled with wires under various conditions. For further study, check out the following parts of the National Electrical Code:

- Article 725 – remote control, signaling, power-limited circuits, classes 1, 2, 3
- Article 760 – fire protection signaling systems
- Article 800 – communications circuits
- Article 820 – community antenna television

INSULATION RESISTANCE

Most of the time, we treat insulation as if it simply did not conduct, unless the voltage is so high that the dielectric strength is exceeded and the insulation breaks down. (Once that happens, the insulation can no longer be trusted, even at low voltages, and must be replaced.)



In other words, we treat insulation as if its resistance were infinite. That may not be strictly true. We can measure insulation resistance by putting a high voltage across it and measuring the resulting current. For example, when a large motor is rebuilt, it is customary to measure the resistance between the windings and the frame.

The instrument used to do this is commonly called a **Megger**, and it includes the necessary current limiting circuitry etc. ("Megger" is a brand name of Megger Group Ltd.)

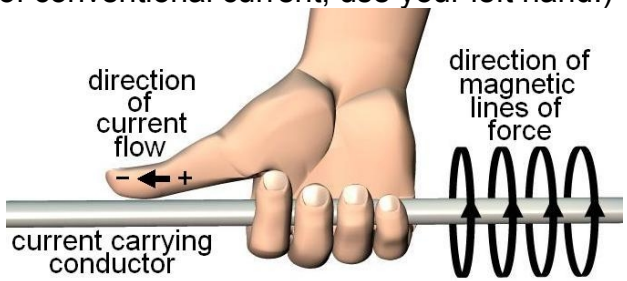
HIGH FREQUENCY OPERATION

It would be nice if wire behaved the same for DC and any frequency of AC, but it doesn't. With AC, other factors come into play, and the higher the frequency, the more significant they become. I'm going to discuss **skin effect** next, which applies to every wire. And later, when we're talking about cables, there will be additional frequency-related issues we'll have to look at.

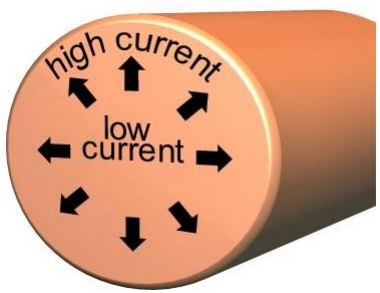
SKIN EFFECT

I've been pretending that current is distributed evenly in a wire, that every square mil carries the same amount of current as every other. With DC, that's true. But with AC, that assumption doesn't hold. As you know, whenever electrons move, a magnetic field is created, and the field is at right angles to the electron motion.

With a wire, this means the magnetic lines of force curve around the wire. In EM1, we talked about the right-hand rule: if you wrap your right hand around a wire, with your thumb pointing in the direction of conventional current, your fingers show the direction of the lines of force of the magnetic field. (If you want to think in terms of electron flow instead of conventional current, use your left hand.)



But with AC, we have to consider **eddy currents**. You remember from EM3 that if a lump of conductive material is placed in an alternating magnetic field, circular currents called "eddy currents" will be induced in it. The reason the magnetic material in a transformer core is broken up into fragments or laminations is to prevent eddy currents.

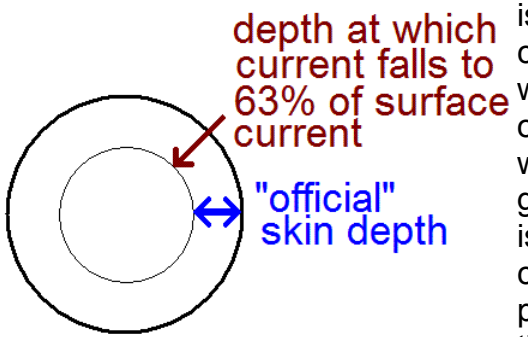


When a wire carries AC current, eddy currents are induced inside the wire itself. These in turn create circular magnetic fields in the wire which push current flow outward, toward the surface of the wire. This is known as **skin effect**.

There's an area in the middle of the wire that doesn't carry its fair share of current. As a result, the wire's overall AC resistance per foot is higher than its DC resistance.

Skin depth is defined as the distance into the wire where current flow falls to 63% of the current flow at the surface.

As frequency rises, skin depth decreases. At 60Hz, it isn't a problem for wires less than ½" diameter, a little larger than 0000 gauge. On the other hand, at 10GHz, the skin is only about 0.66 micrometers, about 26 micro-inches deep. That is, virtually all the current flow occurs within 26 micro-inches of the surface of the wire. At 10GHz, a gold-plated glass rod is about as good a conductor as a gold-plated copper rod of the same diameter.



A tech seldom has to calculate skin effect. Wire and cable manufacturers do all the calculation for you, and publish graphs showing resistance, capacitance and other characteristics at various frequencies for the wire they manufacture. But, just for reference, in case you ever need it, skin depth is proportional to the square root of frequency:

$$\text{skin depth} \sim 2.6/ F^{0.5}$$

...where skin depth is measured in inches. You recall from earlier math discussions that $F^{0.5}$ means "square root of F." Thus, at 10kHz, 10^4Hz, skin depth is $2.6/10^2$ or about 0.026".

Skin depth is necessarily a somewhat arbitrary number, because the decrease in current between the conductor's surface and the depth we define as skin depth is gradual. We can think of a conductor as a hollow tube whose wall thickness is equal to skin depth.

At extremely high frequencies, we may not use wire at all. We may instead use a rectangular metal tube called a **waveguide**.
The inside of the waveguide may be plated with silver, but at high power levels a gold plating is common, though it's not as good a conductor as silver and even more expensive. High-power, extremely high-frequency energy causes the metal plating inside a waveguide to actually move, the way cold-creeping aluminum does. Gold plating has much less creep.

Litz Wire

At radio frequencies, solid wire performs better than stranded wire because stranded wire has greater skin effect problems. However, there's a special kind of stranded wire called **Litz wire** that exists specifically to combat skin effect. In Litz wire, every strand is insulated with a varnished coating.

This breaks up eddy currents in the same way laminations break up eddy currents in a transformer. As a result, there is essentially no overall skin effect, only the skin effect present in each individual strand. Since the strands are very thin, there is no skin effect at low frequencies and greatly reduced skin effect at high frequencies, compared to a solid or stranded wire of the same gauge.

For the tech, the main caution in working with Litz wire is that the ends of each and every strand must be stripped of insulation before soldering. It's not sufficient just to strip the outside of the bundle.

WIRE INDUCTANCE AND CAPACITANCE

You know a coil of wire has inductance, but a straight wire has some too. I haven't been able to find a formula that's worth showing you, because straight-wire inductance is complicated and therefore so are the formulas. Inductance depends on the wire's length, diameter and shape (a flat PC board trace has different inductance from a round wire), and none of the relationships are linear.

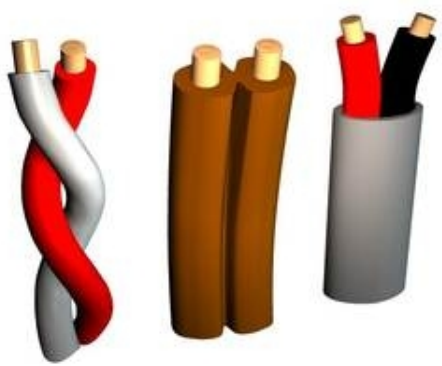
And that's for a single, isolated wire, with current flowing from one end to the other. In other words, it doesn't apply to a circuit, with current flowing in a loop. When you add a second wire with current flowing in the other direction, inductance is affected by distance between the wires and other factors.

In addition, when you have two conductors near each other, there is capacitance between them. All this adds up to a complicated situation that's way beyond the scope of this study guide. I'm just mentioning it to give you a heads-up: these days, techs often work with very high analog frequencies and very high digital data rates, where even the shortest wires have significant reactance. Moreover, a conductor can act as an antenna, and its radiating or receiving behavior depends on length.

This happens whether we intend it or not – a printed circuit trace can make a very effective antenna at high frequencies, leading to no end of trouble. As you proceed to more advanced studies, you'll develop a kind of sixth sense for this.

I've said a lot about single wires; now let's talk about multiple wires bundled together.

CABLES

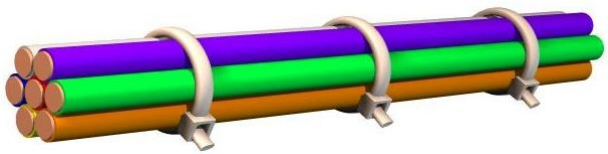


A cable is two or more wires bundled together. If it comes pre-made from a manufacturer, the wires will be surrounded by a **jacket** of rubber or plastic. The entire cable may be encased in a steel spiral if extreme ruggedness is required.

At low frequencies, the reason to bundle wires together this way is simply convenience. At high frequencies, the proximity of signal and ground wires (or, in a balanced circuit, out-of-phase signal wires) brings their inductance and capacitance into play. In a cable, the inductance and capacitance are **distributed** along the length of the cable. This results in the cable having a **characteristic impedance** of so many Ohms. It's not an impedance you can measure with a DC voltmeter, because it only exists in relation to AC signals, and only if the cable's length is at least 10% of the signal wavelengths it's carrying. When a cable is long enough to meet these conditions, it's called a **transmission line** and the impedance of the signal-sending unit at one end and the signal-receiving unit at the other must be the same as the cable's impedance, or part of the signal will bounce back and forth within the cable instead of being properly transferred from source to load. This topic is treated in much more detail in the EM2 study guide, chapter 10.

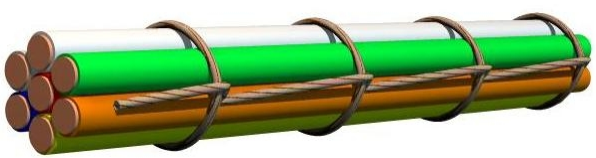
Note that it isn't just cables that have characteristic impedance. At extremely high frequencies, the copper traces on PC boards are transmission lines, and must be treated as such. That's important when connecting the probe of a piece of test equipment. At extremely high frequencies, if you place the probe right at an IC pin, you'll see a waveform that's different from what you'll see if you place it 2” away on a PC trace that's attached to the IC pin.

A cable can be assembled by bundling a bunch of wires together. One method is to put a plastic cable tie around the bundle every few inches. I'm personally a little wary of that method, though I've used it. Most cable ties are nylon, and believe it or not, nylon is partly water. Over several years, as the nylon dries, the cable ties can become brittle. If the bundle is also held in place by other means, brittle cable ties will never matter.

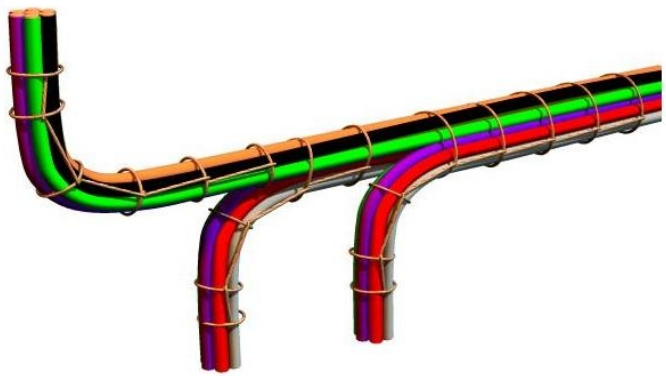


When installing a cable tie, some techs pull it as tight as they can. This is bad practice; in a few years, the cable tie is likely to be much weaker than when new, and it may snap. Just pull hard enough for the tie to firmly grasp the bundle.

The traditional way of bundling a cable is by **lacing** it with wax-coated twine made for the purpose. There are several different ways of making the loops, which depend more on the tech's preference than anything. This technique is older than dirt, but it's so good many techs still prefer it.



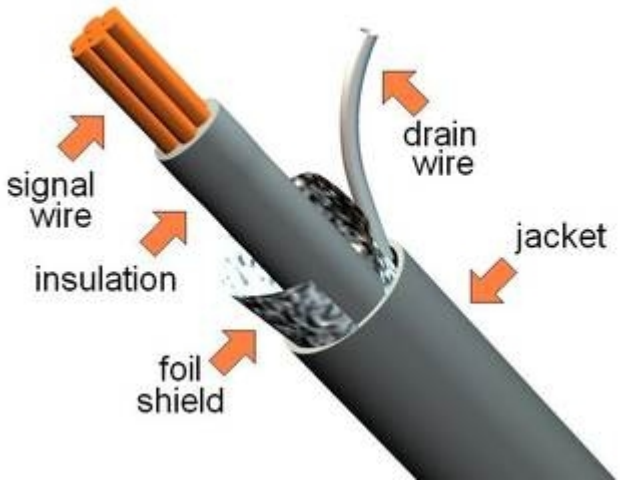
If you're making up a cable out of individual wires, there's no reason they have to all be the same length. Wires can enter or exit the cable anywhere along its length, wherever they need to connect to a piece of equipment. This kind of wire bundle is called a **harness** and the most familiar example is the wiring system in an automobile. If many harnesses of the same kind are going to be assembled, it's worth making up a panel with nails or clips at various points and assembling the harness on the panel, then moving it to the equipment for installation.



COAX CABLE

In coax (pronounced CO-ax) cable, the ground conductor is made in the form of a tube that surrounds the signal conductor. “Coax” is short for **co-axial**, meaning the inner signal wire and the outer ground conductor are on the same axis.

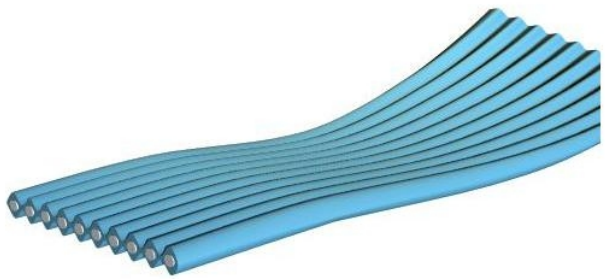
The outer conductor may be braided or, as in the example shown below, may be a metal foil with a **drain wire** running alongside and in contact with it. When connecting this kind of cable, you attach to the drain wire, not the foil.



The purpose of a coax cable is to place the signal wire in a ground-potential environment along its entire length, to protect it from electrostatic noise in the environment. Coax construction also confines the cable's magnetic field, making it resistant to electromagnetic noise.

When discussing noise, we have to be aware that it can go the other direction too: signal can radiate outward from a cable and get into other cables. This is called **crosstalk**, and even though it's a proper signal, when it bleeds into other signals it's noise from their point of view. One way to combat crosstalk is to use coax cables. For example, in a VGA video system, the red, green and blue information, as well as horizontal and vertical synchronization, are all separate signals. To keep them from mixing with each other, a VGA cable contains five separate coax cables, one for each type of signal.

RIBBON CABLE



Ribbon cable is a flat cable with many tinned wires embedded in a plastic insulation side by side. The plastic is ribbed, like zipcord, and for the same reason: to permit the cable to be split and different groups of wires to be routed to different places.

Ribbon cable connectors have IDC contacts spaced the same as the ribbon's conductors. **IDC** is short for **insulation displacement connector**, and what that means is that you don't strip the insulation off the wires. The back of each connector pin has sharp edges that slice through the insulation and make contact with the wire.

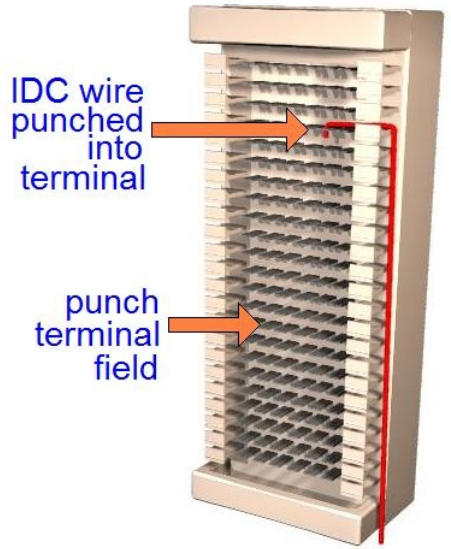
When making up a cable, you put the connector on the ribbon and insert it into a special tool. The tool crunches the connector, causing all the pins to poke through the insulation and make contact with all the wires at the same time. This is called **mass termination**, and the purpose is to make cable assembly much simpler and much faster. It's possible to terminate ribbon cables by mashing the connectors in a vise – watch out for the pins! – but for anyone who does it professionally there really is no excuse for not using the proper tool made for the purpose.

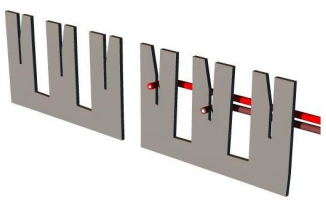
Standard ribbon cable has considerable crosstalk between wires. This can be reduced by using every other wire for signals and grounding the rest. For more critical applications, twisted-pair and shielded ribbon cables are available, but they're clumsy enough that much of the practical benefit is lost, so people typically turn to other cabling methods.

With digital signals, crosstalk doesn't matter unless it's so bad it obscures the difference between 1 and 0. That makes ribbon cable ideal for short runs and parallel data words.

UTP

Many of the connection methods used for **UTP** or **unshielded twisted pair** such as CAT5 cable also use insulation displacement. One common example is the **punch block**, a plastic rectangle containing many rows of terminals. Each terminal has a narrow slot. When a wire is pushed sideways into this slot, it cuts through the insulation and makes contact with the wire. Horizontal rows of terminals are internally connected, so wires punched into adjacent terminals are connected.





PUNCHBLOCK TERMINALS

Originally developed for the telephone industry, punch blocks are a reliable way to connect CAT5-type cable. The main caution is that, for cables carrying very high-frequency analog signals or digital data, a punch block cannot be used because it creates a “lump” in the characteristic impedance of the line. A proper punch block tool is necessary; it's really not practical to do this any other way.

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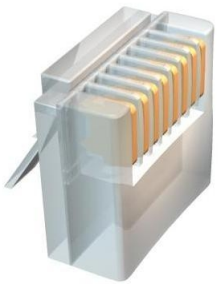
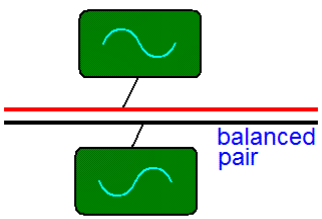
The most familiar insulation-displacement UTP connector is the **modular connector**, another item invented for the telephone industry. Ethernet uses an 8P8C connector. Again, it's necessary to use the proper tool.



Most things that connect via UTP have balanced inputs/outputs. Balancing is a very effective way to fight interference reception / radiation / crosstalk. To recap from EM3, a balanced circuit is one with two wires, where the signal appears as a voltage *difference* across the pair. When one wire goes positive, the other goes negative. From the standpoint of outgoing interference, this cancels most signal radiation, a situation which improves if the wires are twisted. From the standpoint of incoming interference, a balanced circuit that "sees" only the voltage difference across the wires will be "blind" to a voltage that appears equally on both wires, as incoming radiation tends to be.



STP

If a balanced, twisted pair doesn't provide enough isolation, an overall shield can be added. This is known as a **shielded twisted pair** or **STP**. In a cable with more than one pair, the pairs can be individually shielded, if crosstalk between pairs is a problem, or the cable may just have an overall shield to isolate it from the outside world. Wherever a cable shield exists, it must be grounded to the chassis ground of whatever it's connected to or the shield does no good.

(I wonder if STP is used to wire up the computers at the corporate headquarters of Armored Auto Group, makers of STP®. Okay, never mind.)

Properly terminating wires and cables is important, especially if they're handling such high frequencies that improper terminations could reflect signal back toward the source. In chapter 8 we're going to look at interfacing electronic equipment, and we'll study terminations as part of that.

End of chapter 2

EM5 Chapter 3
AC & DC GENERATORS

Objectives of this chapter:

- *summarize electromagnetic induction, including Fleming's rules.*
- *explain why all generators make AC, and how DC generators turn AC into DC*
- *define “slip rings,” “commutator,” “brushes”*
- *explain what is meant by “prime mover”*
- *define “rotor,” “stator,” “field,” “armature”*
- *explain excitation, self-excitation and flashing*
- *describe series, parallel and compound-wound generators and their characteristics*
- *explain the advantages of using the stator for the armature*
- *describe 3-phase power and delta and wye circuits*
- *discuss the special characteristics of automotive alternators*
- *describe how a stable 60Hz can be obtained from an armature whose speed varies*

Motors and generators are electric, not electronic. They've been around since the late 1800s, before the field of electronics even existed, so they're hardly high-tech. However, now that high-power solid state devices are available, those old dogs are being taught new tricks.

Under electronic control, motors and generators are doing their traditional jobs better, doing new things they couldn't do before, and doing it all with less wasted energy. And, because of all that electronic control, technicians today need to know something about motors and generators.

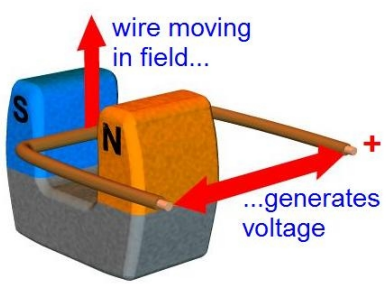
Most of what you'll learn in this chapter and the next is traditional generator and motor science. After all, they haven't changed. What's new is the control technology. We'll also talk about some new motor types in the next chapter that existed only In theory until electronics came along.

MAGNETS, MOVEMENT and ELECTRICITY

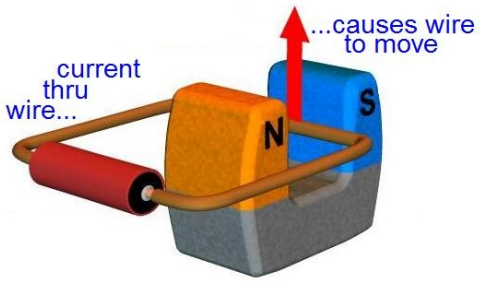
I've put AC and DC generators together in one chapter because, with a few small differences, they are exactly the same. In fact, I could have put AC and DC generators together with AC and DC motors in one big chapter. There is so little difference between motors and generators that some motors will work as generators, and vice versa.

What almost all AC and DC generators and motors have in common is magnets, movement and electricity. (Hey, that would make a great book title. Dibs.)

In the world of electricity, magnets are like the ancient alchemists who supposedly could turn one material into another. Magnets convert movement into electricity and electricity into movement. If we move a wire through a magnetic field, the motion will create a voltage between the ends of the wire. That's a generator. On the other hand, if we send current through a wire in a magnetic field, the wire will move. That's a motor.



GENERATOR



MOTOR

INDUCTION AND FLEMING'S RULES

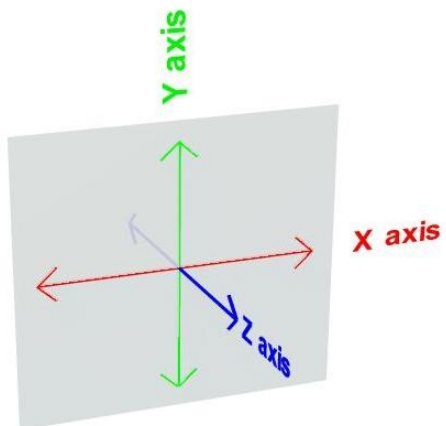
Since this chapter is about generators, here's a couple of words you should learn: **electromagnetic induction**. It happens when:

- a wire moves past a magnet
- a magnet moves past a wire
- a wire is in a magnetic field that's changing in strength, getting stronger or weaker.

When any one of those things happens, a voltage is "induced" between the ends of the wire. The "input" is motion; the output is electricity.

The screwy thing about electromagnetism is that it tends to work sideways. **The direction of electric current flow is at right angles to both the direction of motion and the direction of the magnetic field.**

Is that even possible? Sure. Remember, we live in in three-dimensional space. We've studied and used the X-Y graph, with the X-axis going left to right, and the Y-axis going up and down. But there is also a Z-axis, which we usually don't think of because it can't be put on the graph. It goes toward and away from us, like pins sticking out of the front and back of the graph at the origin. We can show the Z-axis by tilting the X-Y graph a bit, so we're viewing it at a slight angle. Now we can see the Z-axis. And we can see that each of the axes is perpendicular to both of the others.

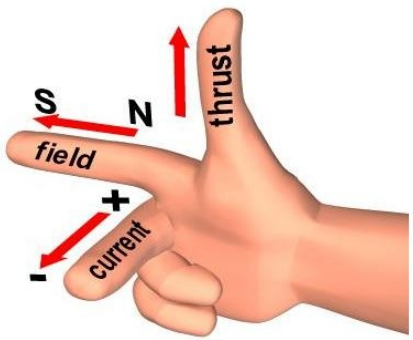


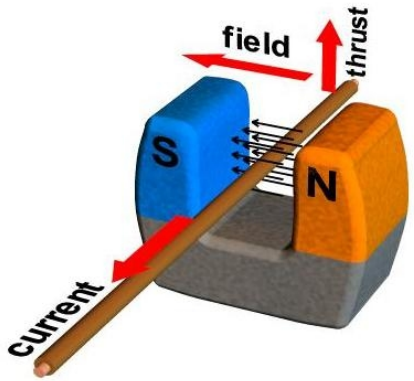
British scientist John Ambrose Fleming did engineers and technicians a favor by inventing a convenient rule to help us remember how the direction of force is related to voltage and magnetic field. Before we go on, you need to make a definite choice whether you want to think in terms of conventional current or electron flow. The Fleming rules for the two are different, and there are also motor rules (next chapter), and you'll get confused unless you choose one or the other and stick with it for these two chapters.

Let's start with conventional current, as Fleming did. We start by holding the thumb and first two fingers of the *right* hand as shown to the right. This gives us three digits pointing in directions that are all perpendicular to each other. The three factors, current, magnetism and force, are assigned to three fingers:

- **C**: the **c**enter figure represents **c**urrent, flowing in the wire from positive to negative .
- **F**: the **f**irst finger or **f**orefinger represents the magnetic **f**ield, pointing in the direction of the lines of force, North to South.
- **TH**: the **th**umb represents **th**rust, that is, movement.

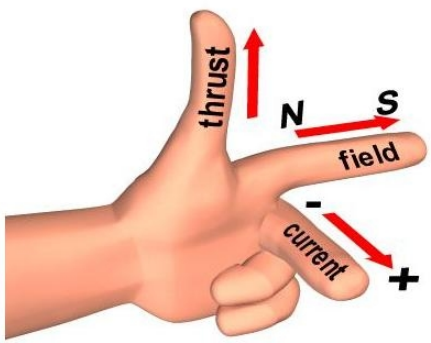
You can find the direction of current flow in any situation by turning the hand until the fingers align with the field and wire. This is called **Fleming's right hand rule for generators**.





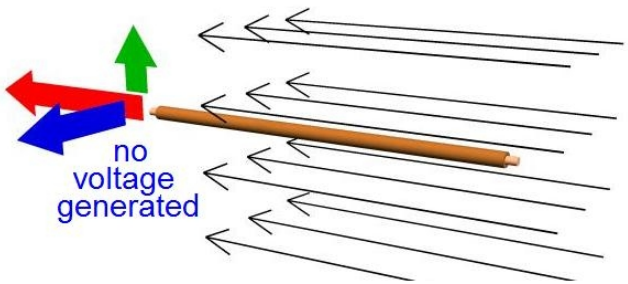
The center finger points in the direction of conventional current flow, from plus to minus.

Some techs, many engineers, and most instructors think in terms of electron flow, from negative to positive. With electron flow, you use the *left* hand. The center finger points in the direction of electron flow, minus to plus. The knuckle is negative and the tip is positive. This is called **Fleming's left-hand rule for generators**.



If you look up Fleming's Rule tutorials on the web, you'll see people explaining it both ways, and neither group seems to be aware the other exists. So now you know. Use whichever rule works best for you.

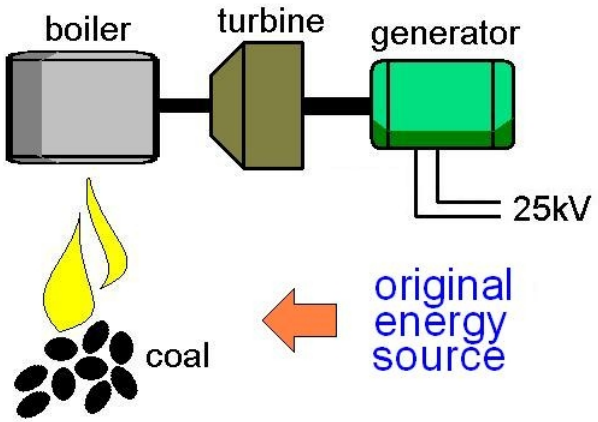
Note that the wire must move *across* the field. If a wire is positioned in the same direction as the lines of force, you can move it in any direction you want and you won't get any induced voltage.



GENERATORS

The modern world couldn't exist without generators to power it. Batteries don't count. Primary batteries run down, and secondary batteries are useless without power to recharge them, which comes from generators. With the exception of solar power, which is only now reaching economic practicality and is a long way from being able to handle the whole job, there has always been only one way to generate large amounts of electricity: by moving magnets and wires past each other.

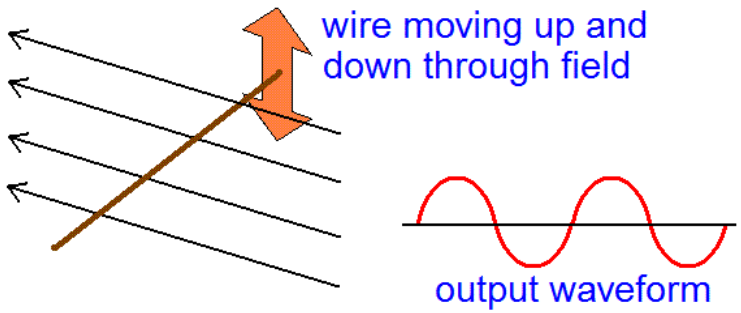
A generating system starts with a **prime mover** which is some other kind of energy, like coal, natural gas, nuclear fuel, wind or water pressure.



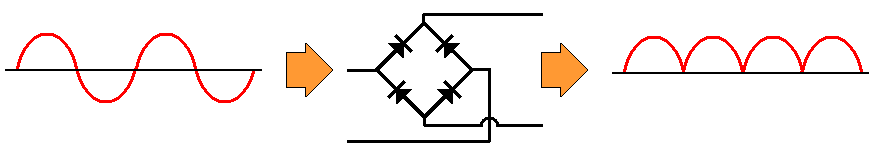
In the case of nuclear, coal or natural gas, heat is converted into steam pressure. A fan or turbine converts this to rotary torque; the torque spins a generator, and we get electricity.

Generators are always AC. Voltage is induced in a conductor only so long as it's in a *changing field* or is *moving relative to the field*. A field can only keep getting stronger for so long until it hits a practical limit; after that the only way it can continue to be a changing field is to get weaker. Likewise, a wire can only move through a field so far before it leaves the field; after that the only way it can stay in the field is to reverse direction. When either of those things happens, the electrical polarity reverses.

Likewise, if the electricity is generated by a wire moving through a field, at some point it's going to be outside the field. If we want to continue to get electricity, the wire has to come back through the field in the other direction, which reverses polarity. (Try it with one of the hand rules and see.) Thus a generator must put out AC.

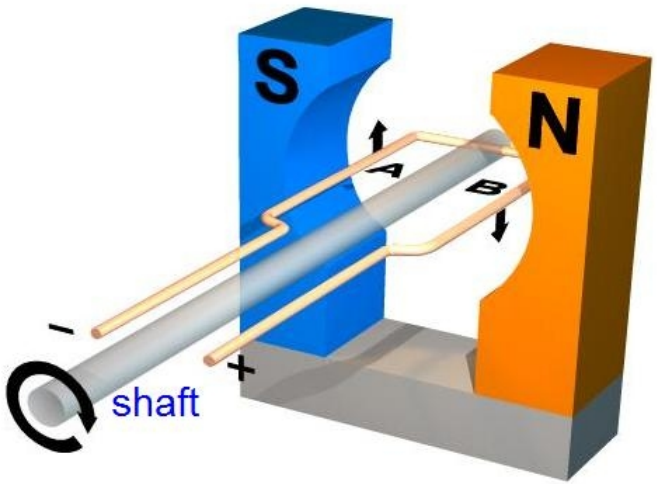


A DC generator is an AC generator with a switching arrangement that changes the electrical path twice each cycle to always steer the positive voltage to the same wire. In EM3 we looked at a solid state version of this switching arrangement, the **bridge rectifier**.



SIMPLIFIED AC GENERATOR

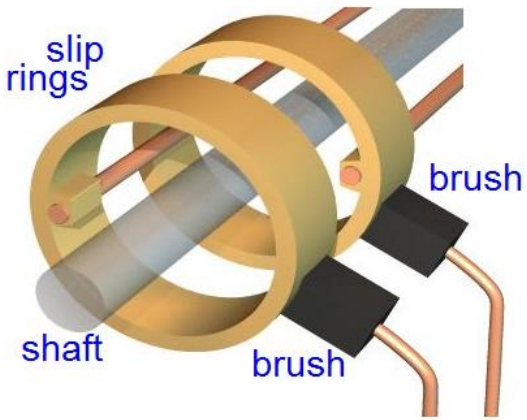
The most basic generator is a wire loop in a magnetic field, mounted on a spinning shaft. I didn't draw the lines of force because they would have resulted in a confusing drawing, but you know they go from the North pole, across and through the wire loop and shaft, to the South pole.



Wire section "A" on the left is moving upward through the field, and wire section "B" on the right is moving downward through the field. That means the voltages induced across these two wire sections will be opposite polarities. If we connect them in series, so they form a loop, we'll get an AC voltage that's the sum of the two individual voltages across A and B. Note that, when the rotation passes 90 degrees, so B starts going up and A starts going

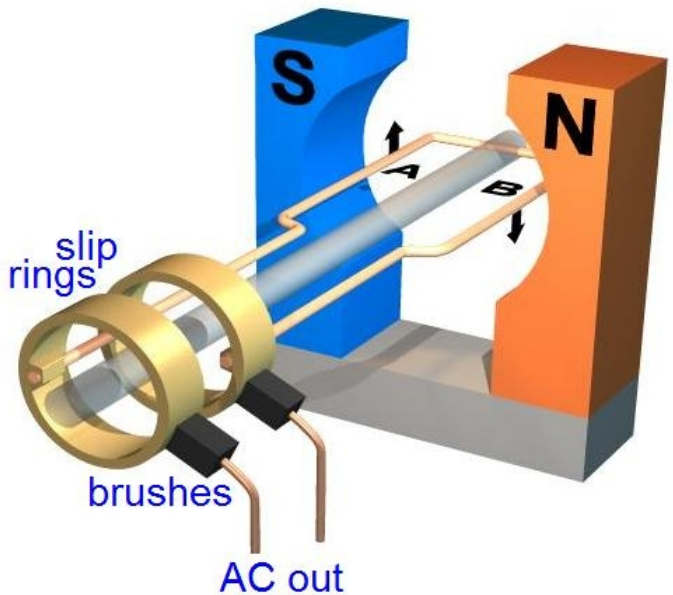
down, the polarity across the wire ends reverses. This reversal will happen twice with each complete rotation, which is another way of saying that the output polarity will alternate – it will be AC.

The practical problem with this arrangement is making electrical connections to a loop that's constantly spinning.



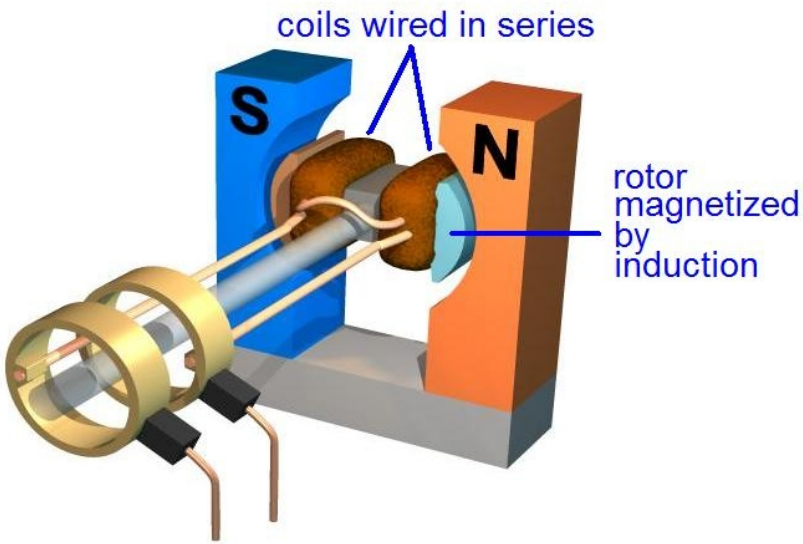
You can't attach wires. Instead, the loop is attached to brass or bronze **slip rings**, sometimes called **collector rings** (because they "collect" the generated electricity) which spin along with it. As they rotate, they maintain continuous contact with stationary **brushes** that provide a way to connect to the generated voltage.

Brushes are so named because, at one time, the problem of maintaining good, continuous contact with spinning slip rings was solved by using brass or bronze brushes, with enough bristles to insure that some of them were always in contact with the slip rings. Nowadays, we use hard blocks of **graphite**, which is essentially compressed carbon. Carbon isn't that good a conductor, but if we use big fat blocks of it, voltage drop can be minimized. Graphite is a lubricant, so it automatically keeps the rubbing mechanism from grinding itself to destruction. If the parts are well made, they can give many years of trouble-free service.



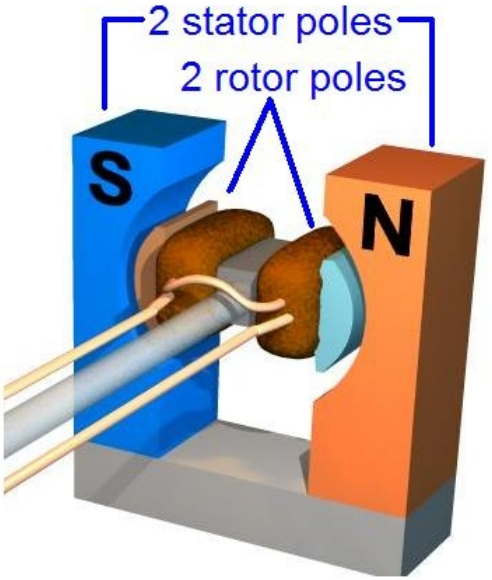
The complete AC generator shown to the left is a very primitive represent-ation; nobody would actually try to build one this way. First, we'll get a lot more voltage if we use a coil of wire instead of a single turn. Second, we know that electromagnetism tends to get a lot more efficient if we put a ferromagnetic slug in the middle of the coil, so the field doesn't have to jump through a long air gap.

In a real generator, the conductor is wound on laminations made of soft iron (or silicon steel, which is better), tremendously increasing efficiency. Note the colors in the illustration below that show this part has been magnetized by **magnetic induction**, which we studied in EM1.



The spinning part is called the **rotor**, because it rotates – duh – and the part that provides the external magnetic field is called the **stator** because it's stationary – duh again. The induced rotor magnetization switches direction and then switches back again once for every complete rotation. The changing magnetization in the rotor is what induces voltages in the coils.

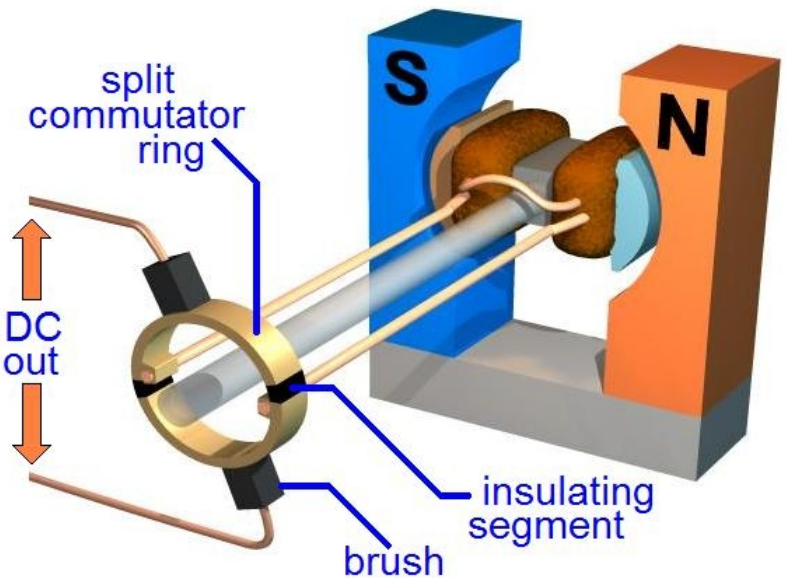
In the generator shown here, the rotor and stator each have one set of **poles**. The stator poles are either permanent magnets or electromagnets whose polarities do not change; one is always North and one is always South.

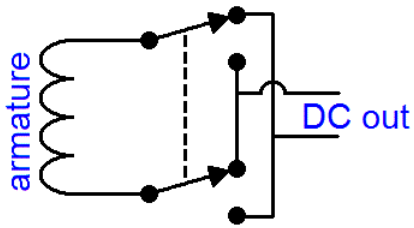


The part where the voltage is generated, the rotor in this case, is called the **armature**. The part that supplies the magnetic field, the stator in this case, is called the **field**, fancy that. In small generators, that field is supplied by permanent magnets. A generator using permanent magnets is called a **megneto** (mag-NEE-to). In larger generators, the field is created by electromagnets, whose coils are called **field coils**.

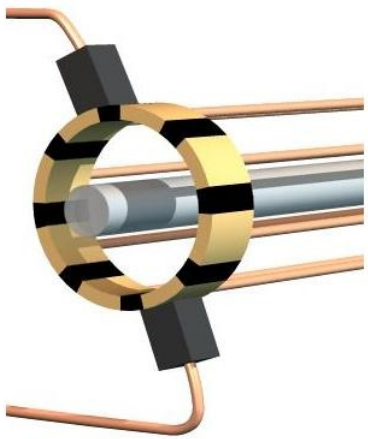
DC GENERATOR

As noted above, a DC generator is made by rectifying the output of an AC generator. For the better part of a century, between the invention of the generator and the invention of high power solid state rectifiers, this was done by a mechanical switching arrangement. Instead of using two slip rings, the wire coil in the armature is connected to a single ring which is split into halves. Brushes on either side make contact with the ring.



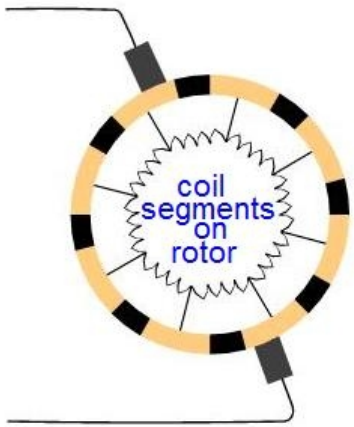


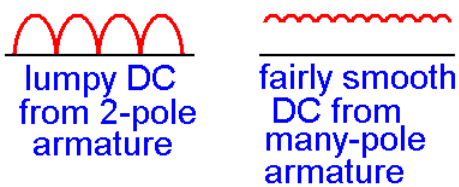
At precisely the point where the AC waveform crosses zero, connections between the ring and the brushes reverse. This steers the output so the polarity is always in the same direction. This mechanism is called a **commutator**. Functionally, a commutator is equivalent to a DPDT switch. By changing positions twice each cycle, AC is turned into DC.



Of course, it's lumpy DC. In EM3, we learned how to smooth out the waveform using inductors, capacitors and solid state regulating circuits. But before that technology was available, semi-smooth DC was obtained by splitting the armature winding into many coils connected to many commutator segments, so the handoff at the switch points was smoother.

As shown to the right, there is one continuous winding tapped at many points. As each section of the winding reaches the point in its rotation where its polarity reverses, the commutator switches that section. Switching occurs when the voltage across adjacent commutator sections is zero, so there's little sparking. The output is fairly smooth DC.



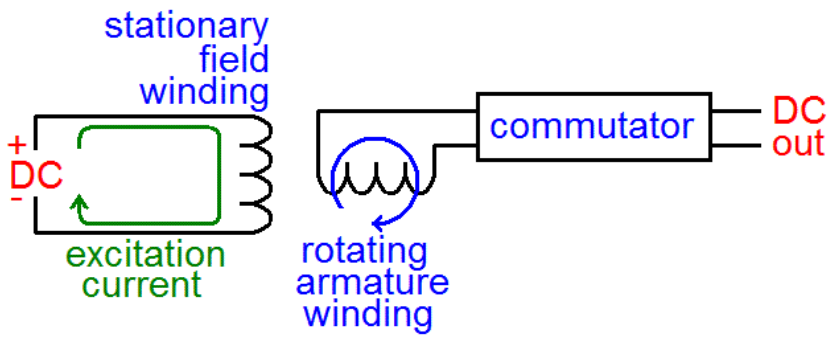


In actual generators, DC is smoothed further by laying part of each coil segment over part of the next one. The inductive reactance typical of electromagnets also contributes to smoothing.

You'd assume AC to DC conversion would be handled by rectifiers today, but that's not always the case. A rectifier has a voltage drop and a power loss, and you'd still need slip rings to get the power out. The old-fashioned commutator is, in many ways, more efficient. Edison was wiring cities with DC power in the late 1800s, seventy-odd years before high power rectifiers became available.

MAGNETIZING THE FIELD IN A DC GENERATOR

There are several ways to make the field magnets. The obvious way is to just use permanent magnets, but in Edison's day, there was no such thing as a strong permanent magnet. So Edison and others created strong magnets the only way they could: by building electromagnets. By now, we've had strong permanent magnets for about sixty years, and really strong ones, called **rare Earth magnets**, for around 35 years. However, for generators on the scale of those used in power plants, these magnets would be impossibly expensive. So large generators still use electromagnets for the field.

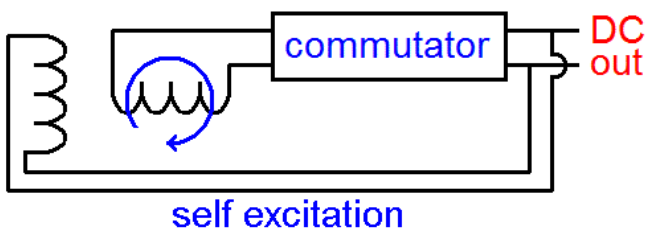


The current needed to magnetize the field is called **excitation current**. To make a non-alternating stator field, the excitation current must be DC.

Obviously, the output power is very much larger than the power consumed by excitation; otherwise, the whole exercise would be as pointless as a ballet dancer at a barn dance.

We could get the excitation DC from a battery, but the battery would run down. But with a DC generator, there's a way to make the generator supply its own excitation current.

If we can get some DC to start with, we can apply it to the field coil and excite it, and the generator will start making DC. From then on, we can tap off some of the generator's own output and use it to keep the field coil energized. This is called **self excitaton** and it's the usual way of magnetizing the field, except for small magnetos that use permanent magnets for the field.



It is not usually necessary to supply initial DC excitation. Any ferromagnetic material that has once been magnetized will usually retain a small amount of **residual magnetism**, which is enough to get things started. If there isn't enough residual magnetism, momentary application of DC from a battery will do the trick. This is called **flashing** the field.

VOLTAGE REGULATION IN A DC GENERATOR

We would like a generator's output voltage to be predictable, otherwise it's kind of useless. Unfortunately, that doesn't automatically happen.

Suppose we have a certain generator, with a certain number of turns of wire on the rotating armature, turning at a certain speed, putting out a certain voltage. If we want to change that voltage, there are three ways of doing it.

The first one can't be done while the generator is running: change the number of turns in the armature winding. More turns, higher voltage.

The second can easily be done: change the speed of the armature. Higher RPM, higher voltage.

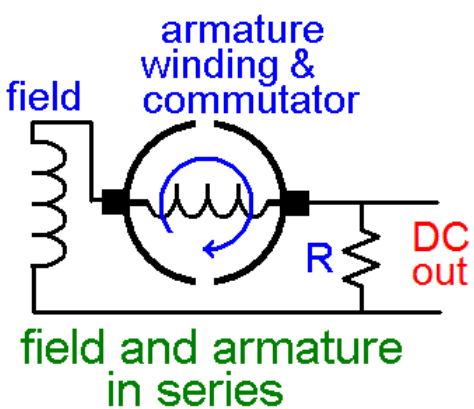
The third also can easily be done, if we're using electromagnets for the field: change the strength of the field. Stronger field, higher voltage.

So, if we *don't* want the voltage to change, we have to keep the number of turns in the armature winding the same (no problem there), we have to keep the speed the same (a little more complicated), and we have to keep the field strength the same (this is where the problem lies).

One other factor affects output voltage: the load. In a magneto, with permanent-magnet field poles, if the load increases, voltage will sag a little as you'd expect, due to resistance in the armature winding. If the load decreases, voltage will rise a little. These are minor variations. But when we're using a field coil instead of permanent magnets, and the excitation current is derived from the generator itself, load changes cause serious voltage variations.

SERIES, PARALLEL AND COMPOUND-WOUND GENERATORS

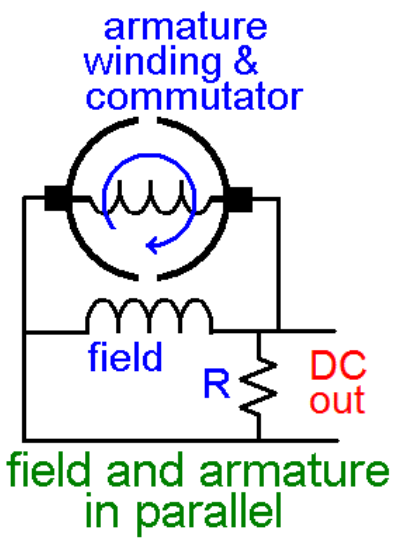
Suppose we connect the field coil in series with the armature – this is called a **series-wound** generator. **R** represents a permanent load. There has to be some load at all times, because some current has to flow through the field coil to keep the generator in operation.



Now suppose we connect an additional load. This causes current through the field coil to increase, which will increase the field strength (unless the stator is already saturated), which will increase output voltage, which will increase current further. In other words, as the load increases – as current rises – the voltage rises. And if the load is a resistor, current is proportional to voltage, so rising voltage will cause current to rise further.

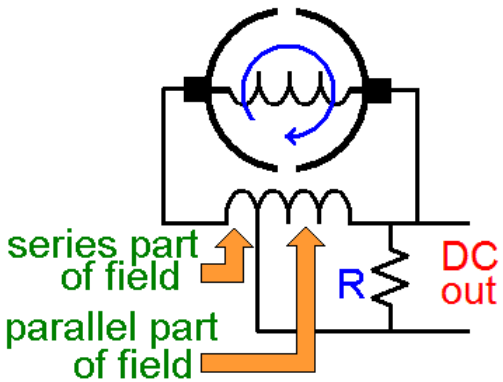
If you've completed the EM3 study guide, you know what this is: positive or regenerative feedback. And you know that positive feedback works against stability. In a series-wound generator, voltage and current increase until the iron in the field saturates. That's one way to stabilize voltage, but a better way is simply to not use series-wound generators. And, in fact, almost nobody does.

Suppose instead that we connect the field coil across the armature – this is called a **parallel-wound** generator. Now feedback works the other way.



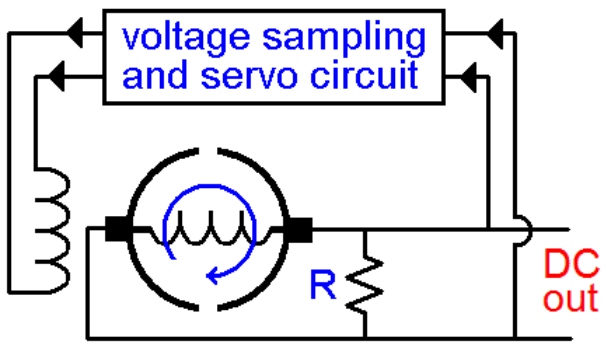
If we connect a heavier load, that will drag down the output, which will drag down the voltage across the field, which will weaken it, reducing the output further. This isn't as unstable as the series-wound generator, but it's still not ideal.

We need to do a balancing act. We need the field coil to be partially series connected and partially parallel connected. This is called a **compound wound generator**. If we do it right, the voltage-boosting and voltage-sagging effects will cancel, and we'll get a nice stable output that doesn't change much when the load changes. This is a widely used traditional way of stabilizing output voltage.



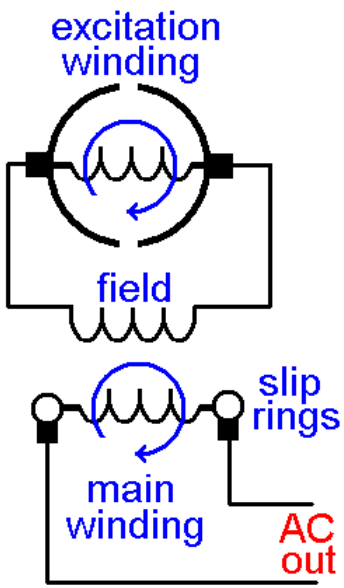
Most of the output voltage comes from the parallel part of the coil, so it's the largest. The series winding has comparatively few turns, and since all the load current flows through it, it's made of heavy wire to minimize losses. The series winding isn't really there to generate a lot of power, it's just there to cancel the sagging tendency of a shunt-wound generator.

That's most of what you need to know about a traditional DC generator. There are a million details, of course, but those are for generator designers to worry about. Where a modern generator differs from an old-fashioned one is that field current may be controlled electronically. This permits more precise voltage control and regulation, especially if the electronic circuit monitors the output voltage and uses that to adjust field current. This is a form of feedback, but in this case it's negative or corrective feedback. (This kind of control is called a **servo loop**. Refer to the EM4 study guide.)



MAGNETIZING THE FIELD IN AN AC GENERATOR

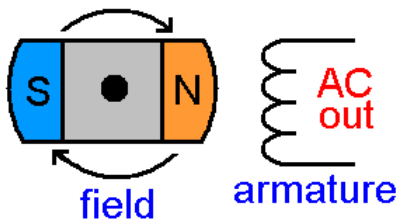
An AC generator can self-excite too, but it's a little more complicated, because the excitation current has to be DC. Some generators have both slip rings, for the main AC output, and a commutator to draw off a little DC for the field coil. In modern generators, the commutator may be replaced by an electronic commutation system consisting of a bridge rectifier.



If the excitation voltage is derived from a separate excitation winding on the armature as shown to the left, so as to provide an independent excitation source, output voltage is more stable, sagging only a little on heavy loads. Another way of avoiding the positive feedback problem, often used with very large generators, is to provide a small DC generator whose only function is to generate the field current for the large generator.

ROTATING FIELD, STATIONARY ARMATURE

Many AC generators reverse the arrangement we've been talking about: the rotor is the field, which is magnetized, and the stator is the armature, where the electricity is generated. There isn't much point in doing this with a DC generator, because that just means the simple commutator is gone and we have to turn AC into DC by a more complicated method. But there's a big advantage to making large AC generators with the stator as armature.



Suppose the rotor / field were a permanent magnet. Output would be taken directly from the coil wound on the stator, which is not moving. This would totally eliminate slip rings.

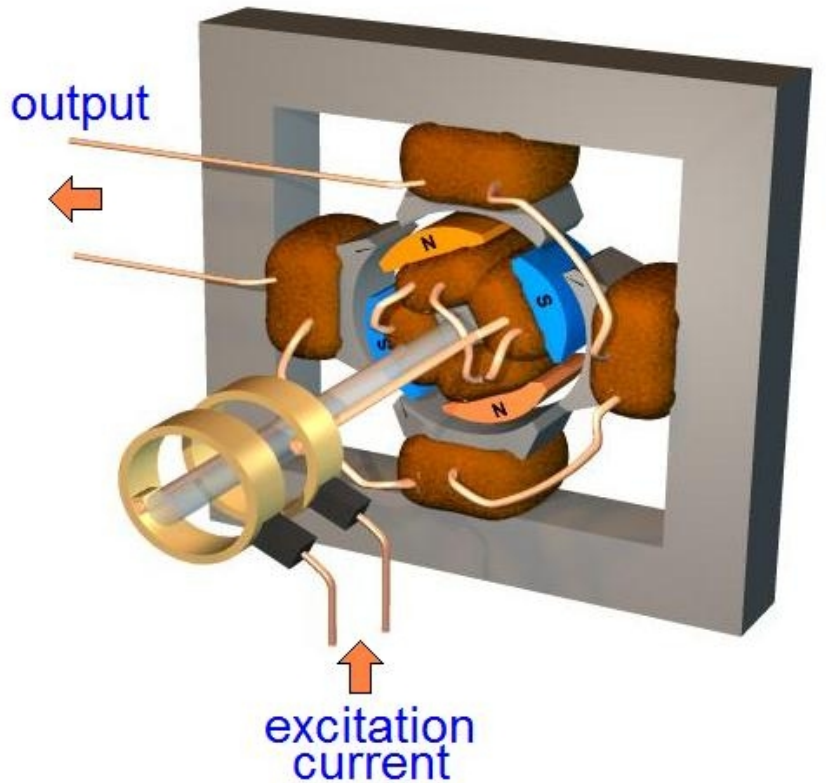
In the humongous generator you'd find in a power plant, a humongous permanent-magnet rotor isn't practical. The rotor has to be an electromagnet, so we're stuck with slip rings again. We still get a benefit, though. The slip rings now only have to carry excitation current, instead of carrying the entire output of the generator. The field coil can be relatively light, while the heavy conductors of the armature are securely mounted on the stator.

AC GENERATOR SPEED

We usually can't run an AC generator at any speed we happen to like. Things like AC motors expect to see 60Hz AC (50Hz in some other parts of the world) and may not work right if the frequency is different. And traditional motor-driven clocks are locked to the power line frequency, so if we want them to tell the right time, the generator must put out exactly 60Hz. Output frequency depends on armature speed. A 2-pole, 60Hz generator must turn at 60RPS (revolutions per second), 3,600 revolutions per minute. This requires the constant attention of a human operator or, nowadays, an electronic servo circuit that adjusts the throttle on the engine (of whatever type) that drives the generator.

MORE POLES

However, we can choose a lower speed by building the generator with more poles. The more poles the generator has, the more poles the magnetized rotor moves past in a second, and the higher the output frequency. If we want to scale that back to 60Hz, we slow down the rotor. A 4-pole generator like the one shown to the right would turn at 1,800RPM. An 8-pole one would turn at 900RPM. My little town gets its power from monster generators far away, like most towns today. But for backup, we still have a pair of 4-megawatt generators from the 1940s that turn at 360RPM, 6 turns per second.

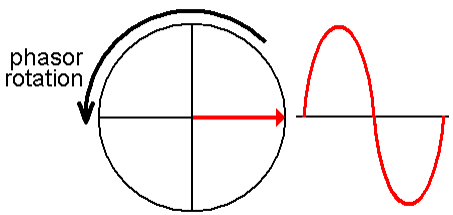


Note that in the 4-pole, 1800RPM generator illustrated above, the coil polarities are arranged so alternate poles have alternate polarities. Excitation current is DC, so the rotor poles stay the same. Stator poles are inductively magnetized, and they flip four times per revolution, creating a 60Hz AC output.

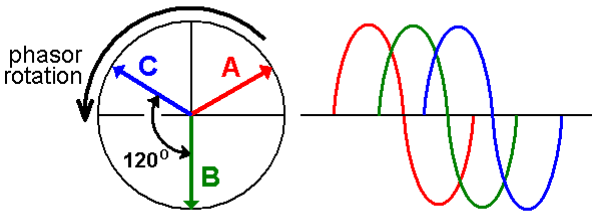
THREE PHASE POWER GENERATION AND DISTRIBUTION

The nation's electrical power distribution system is usually called the **grid**. The grid supplies not one AC sine wave, but three.

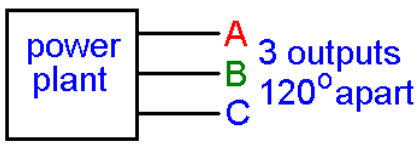
In EM2, we talked about **phasors**. To review: a phasor is an arrow that rotates around the zero-point of an X-Y graph in a counterclockwise direction. The vertical position of the phasor's tip at a given instant, its position relative to the X-axis, represents voltage at that instant. If we plot that value over time, we get a sine wave.



Physically, the significance of the sine wave's shape is that it represents smooth, unchanging circular motion plotted against time. Electrically, its significance is that the sine wave is the only waveform that is pure, containing energy only at the primary phasor rotation frequency, without anything else mixed in. People who design generators try to design them so they put out pure sine waves. AC power that consists of a single sine wave, like the power that comes from the 2-pole generators we've been talking about, is called **single-phase** power.



Suppose we have three phasors, all rotating counterclockwise at 60Hz, but offset from each other by 120 degrees. If we plot that over time, we'll get three sine waves displaced from each other by 120 degrees. This is how power plants generate power – as three separate sine waves, 120 degrees apart, on three separate wires. This is called **three-phase** power.



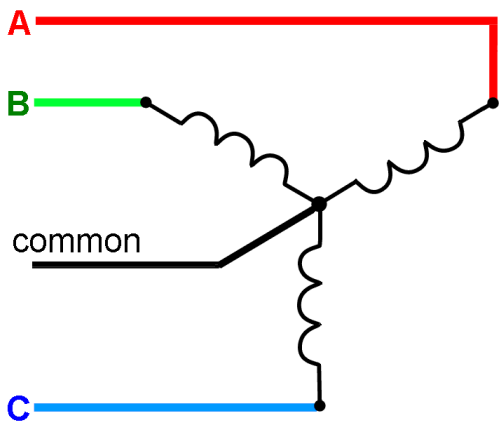
The three phase generating system exists because three-phase motors exist. Nearly all motors of 3 horsepower and over are 3-phase, for reasons we'll discuss in the next chapter. Industry has long since standardized on 3-phase motors, so that is what power companies have to supply.

A 3-phase generator has a 6-pole armature at minimum, wound with three sets of coils, with opposite coils connected in series. In the schematic diagrams on the next page, the coils are drawn at 120-degree angles to each other to represent their phase angles.

There are two ways to connect three generator coils in a 3-phase system: the **wye** and the **delta** configuration.

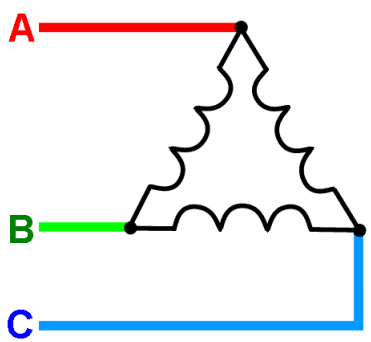
THE WYE CONNECTION

In the wye system, one end of each of the coils is connected to a common wire, and the other ends correspond to the three phases. It's called a wye connection because the three coils together look like a "Y."



THE DELTA CONNECTION

If only 3-phase loads will be connected, there is no need for a common wire. The delta system is so named because the diagram looks like a Greek Delta.



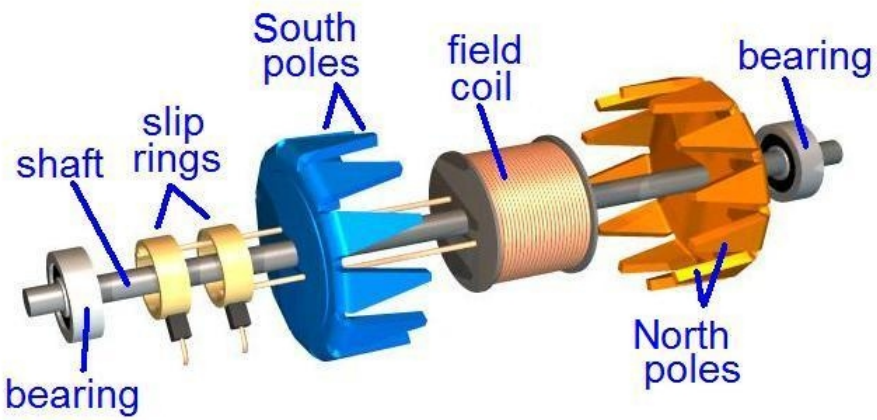
In a generator where the rotor is the armature, the delta connection has the advantage that only three slip rings are needed to bring out the power. Also, for reasons we'll discuss in chapter 5, the delta connection involves more turns of smaller-gauge wire. This is a bonus where current is very high, as it is in large power plants.

AUTOMOTIVE ALTERNATORS

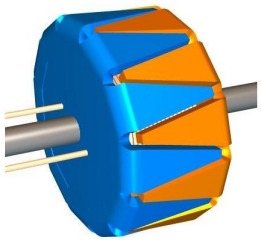
Alternator is another name for an AC generator. We call the generators used in cars alternators, which is a bit strange because of course a car's alternator puts out DC thanks to steering rectifiers. In a car's alternator, the rotor supplies the rotating magnetic field and the stator is the armature.

A car's alternator works in an unusual environment. Since engine speed varies from, say, 200 RPM to at least 4,000 RPM, a 20:1 ratio, and since the alternator is driven by the engine, the alternator speed also varies by at least 20:1. I mentioned earlier that voltage varies with speed, but there's actually a law you might as well know. **Faraday's law** states that **a generator's output voltage varies with the number of turns in the windings and the speed with which those windings move through the field**.

Obviously, if an alternator's speed varies by a 20:1 ratio, that would suggest that the voltage should vary by a 20:1 ratio. Without some form of intervention, an alternator that puts out 14V at idle would put out 280V at highway speed! That's not going to work. Before I show you how this problem is solved, you need to see how an alternator is built. The illustration below shows the rotor, which is the field. What I haven't shown is the armature, where the electricity is generated, which consists of stationary coils spaced around the rotor. You'll just have to imagine those.

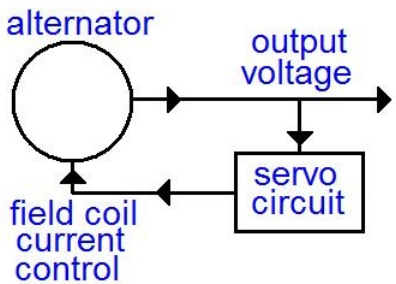


The rotor assembly above is exploded, so you can see the parts. Normally, the field coil, south pole unit and north pole unit are sandwiched together. The pole fingers, which are called **claw poles** for obvious reasons, fit together like folded hands.



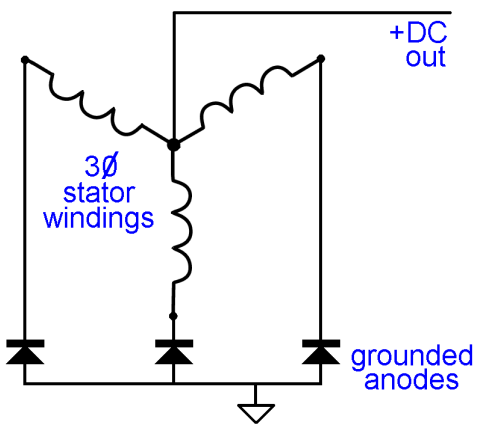
DC current flows through the slip rings to the field coil, magnetizing it. The pole units are soft iron, and since they're on opposite sides of the coil, they are oppositely magnetized. As they spin, North and South poles alternately pass armature coils near them, inducing an AC voltage in the coils.

The key to alternator voltage regulation is that there are three major factors that control voltage, not two. Faraday mentioned number of turns and speed of rotation. The other factor is how strongly the field poles are magnetized. If we reduce current to the field coil, the poles will lose some of their magnetization and less voltage will be produced. If we can set up a circuit to automatically lower excitation current as speed increases, the alternator can have a fairly constant output voltage.



How would you do that? Negative feedback, right. A car has a **voltage regulator** – these days, built right into the alternator – that watches output voltage and adjusts excitation current as needed to keep the voltage within set limits. If you went thru the EM4 study guide, you'll recognize this as a sort of servo system.

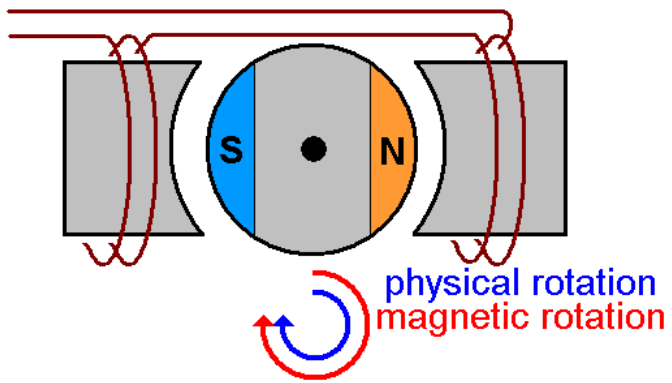
An automotive alternator's armature / stator typically uses a 3-phase wye circuit. The AC output is turned into DC by three rectifiers that are press-fitted into the metal alternator case, using it as both electrical ground and heat sink. When a 3-phase source is rectified, the DC output is much less “lumpy” than with a single-phase source and requires little filtering. The common junction point of the wye is the 12V output, with the rectifiers in the ground circuits of the three windings. The rectifiers are backwards from most press-fit rectifiers: their cases are the anodes. This permits the cases to be grounded directly to the chassis without insulating washers or grease.



GETTING 60Hz FROM A VARIABLE SPEED ROTOR

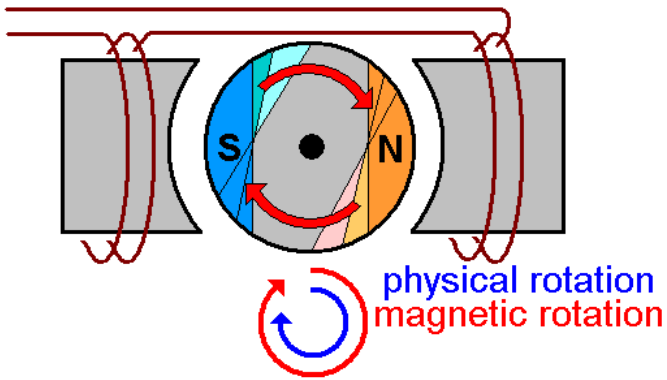
Back in the day, getting exactly 60Hz out of a generator just meant that the power plant engineers had to pay attention to rotor speed. Now that we're trying to harness alternate energy sources, it isn't so simple. For example, when a wind turbine supplies power to the AC grid, not only must its output be 60Hz but it must be in phase with the voltage that's already on the grid. As everyone knows, a windmill's speed of rotation changes when wind speed changes. So there has to be a way to convert the AC output of the generator, which may be any frequency, to a precise 60Hz.

The obvious thing would be to rectify the AC into DC, filter it, then turn it back to AC using pulse width modulation (PWM) techniques. With today's circuitry, that can be done with better than 90% efficiency. However, there is another method that is often more practical.



Suppose the rotor is the field, and suppose it has two poles. Under normal conditions, it would be electrically magnetized, and the magnetic field would spin at the same speed as the physical rotation speed of the rotor.

Now suppose the rotor is soft iron, wound with three coils at 120 degrees. If we feed these coils with 3-phase AC, we can make the rotor's magnetization turn at a different rate than it's turning physically.



Suppose the rotor is turning at 55 RPS, which is 3,240 RPM. If we cause the rotor's field to rotate at 5 RPS, relative to the rotor itself, the stator will experience 60 magnetic cycles per second, which is the rotor's mechanical speed of 55RPS plus its magnetic field's rotational speed of 5RPS. That will create an AC output of 60Hz.

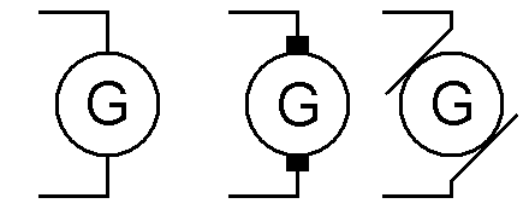
This frees us from the requirement to maintain a 60RPS rate of rotation. We can spin the rotor at whatever speed we want, and the electronics will make sure that 60Hz power comes out.

This has become a widely used technique in very large generators. The advantage is that the rotor speed, instead of being tied to the line frequency, can be whatever speed uses the input energy most efficiently. Usually, in a large generator, the necessary conversion circuitry is mounted right on the rotor and spins around with it. Energy savings can be very significant.

This is one of those things that's always been possible in theory but has only become practical recently, as efficient, fast-switching, high-power FETs and IGBTs have become available. So we've come full circle, to something I said at the beginning of the chapter: modern power generation and distribution needs electronic technicians.

GENERATOR SYMBOLS

In a schematic diagram, a generator is represented by a circle with a “G” in it. If the output comes from the rotor via brushes, the brushes may be shown. Motor symbols are the same, with “M” in place of “G.”



End of chapter 3

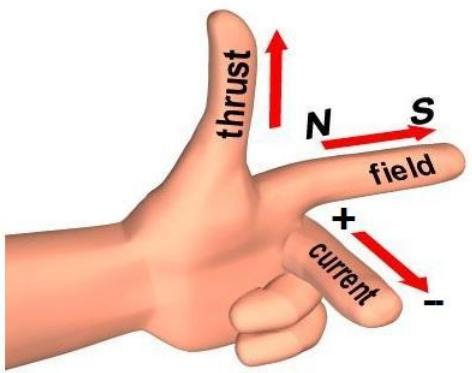
EM5 Chapter 4
MOTORS

Objectives of this chapter:

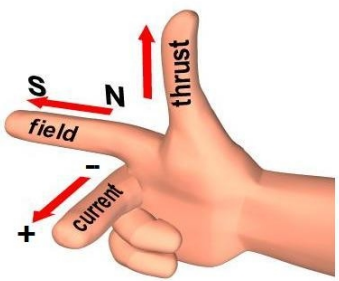
- *give left-hand and right-hand rules for motors*
- *describe the following motors: permanent magnet, series wound, parallel wound*
- *compare starting current to run current*
- *describe universal motors*
- *describe the operation of polyphase AC motors*
- *explain what a "synchronous" motor is*
- *explain what an "induction" motor is*
- *define "slip"*
- *discuss "pullout," "stall," "locked rotor"*
- *explain the operation of shaded pole, capacitor start, capacitor run and split phase motors*
- *give common AC motor speeds and the corresponding numbers of poles*
- *describe "horsepower" and how it is measured*
- *describe AC and DC motor braking*
- *give two methods of speed control for an AC induction motor*
- *explain how to reverse direction in AC and DC motors*
- *describe brushless DC motors*
- *describe stepper and linear motors*

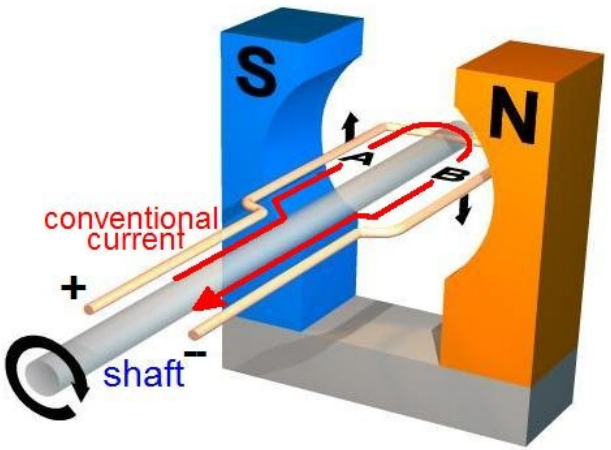
We've seen how a wire moving through a magnetic field generates electricity. Now let's look at the other side of that process: how current flowing through a wire in a magnetic field creates motion.

Once again, the field, the movement and the current are all at right angles to each other. However, we've flipped cause and effect, which means the Fleming laws reverse. For conventional current, we use a right hand rule with generators and a left hand rule with motors. The illustration to the left shows **Fleming's left hand rule for motors**. The labels are the same as with generators: the center finger points in the direction of current, with the knuckle positive and the tip negative. The forefinger is the field,



pointing North to South. The thumb is the direction of thrust. If you'd rather think in terms of electron flow, you'll be dealing with the left-hand rule for generators and **Fleming's right hand rule for motors**.



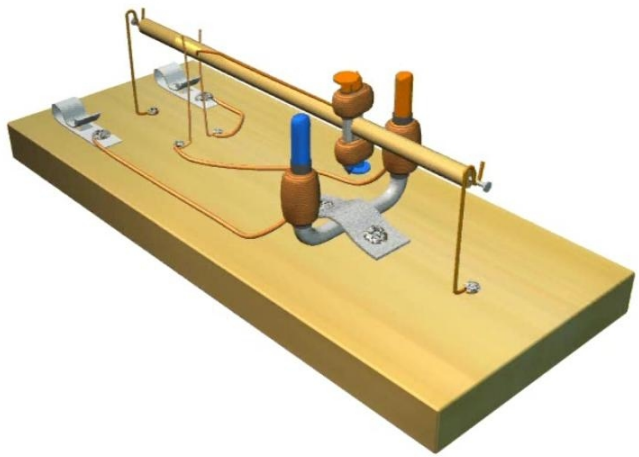


Suppose we take the single-wire-loop generator from the last chapter and, instead of pulling current out of it, put current into it. We'll make the left-hand connection positive, so conventional current will flow clockwise around the loop. The left side of the loop at "A" will move up and the right side of the loop at "B" will move down, creating a twisting motion.

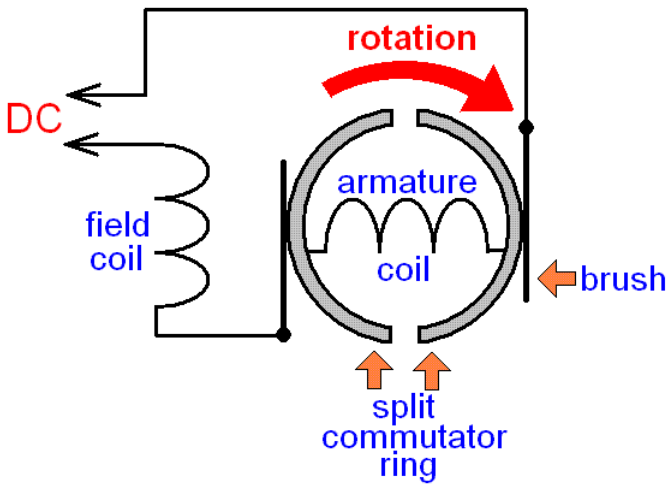
We've seen that an AC generator is simpler than a DC one, because the DC generator requires a commutator. In the case of motors, the situation is reversed. It's obvious how a DC motor with a commutator works. On the other hand, nobody thought there was any way to build a practical AC motor until Tesla came along. So we're going to study motors in the same order that they were developed: DC motors first.

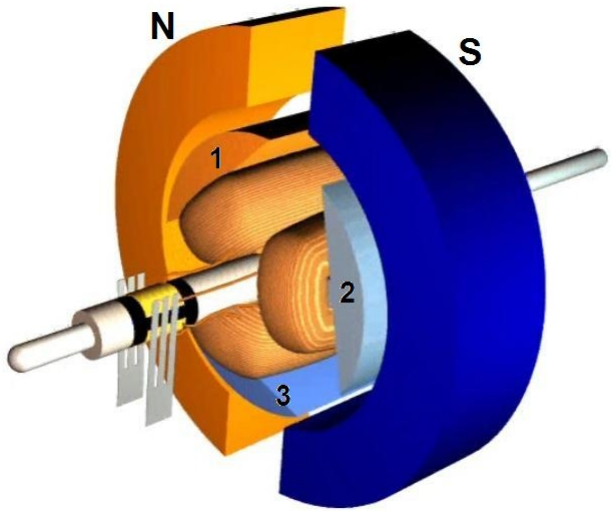
A SIMPLE DC MOTOR

In a real-world motor, the rotor won't just be a wire loop but a coil wrapped around a piece of ferromagnetic material such as iron or silicon steel. Here is a motor that's built by elementary school students in a class at the Museum of Broadcasting in Minneapolis, using a U-bolt for the stator and a couple of iron nails for the rotor. The field generated by the stationary field coil and the field generated by the rotating armature pull on each other, causing the rotor to turn. When the two parts reach the point where they're "lined up" – where North pole (orange) of the rotating part is next to the South pole (blue) of the stationary part, and vice versa – a commutator switches the polarity of the rotor coil's current, which causes the armature to suddenly swap magnetization, North becoming South and vice versa.



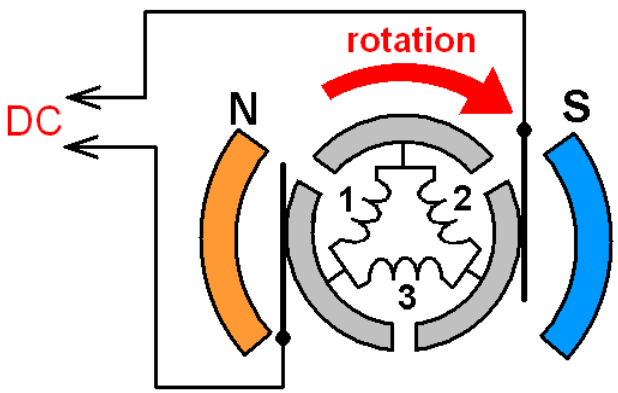
This keeps happening and the motor keeps turning. It wouldn't surprise me if you said you'd built something like this in elementary school. This has been the basic design of DC motors since before Edison.



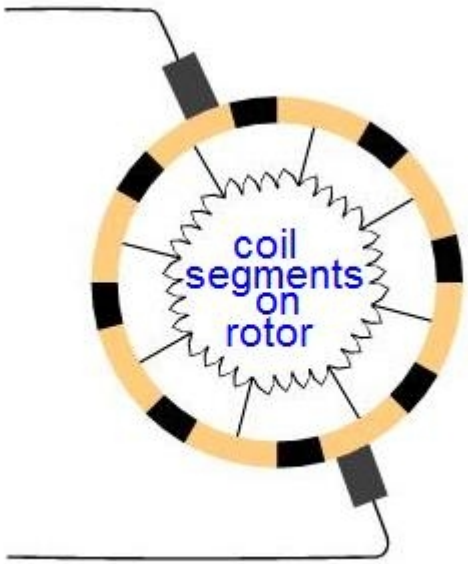


PRACTICAL DC MOTORS

Most DC motors do not have just two rotor poles. For one thing, if the rotor stops right at the point where the commutator is about to switch polarities, it won't start by itself. Real-world motors usually have at least three poles. The illustration to the right is a type of permanent-magnet motor used in everything from toys to DVD drives. There are two permanent-magnet field poles and three armature poles. Toy motors can be bought surplus for under a dollar; it would be worth taking one apart to see how it's made.



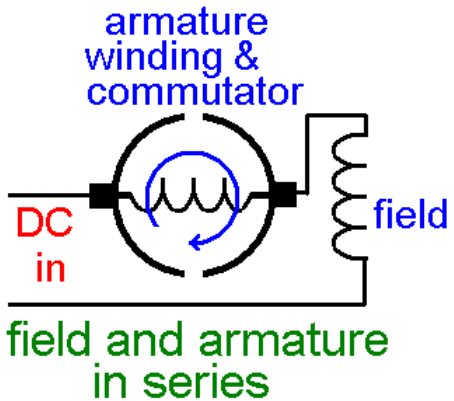
Appliance motors, like those found in vacuum cleaners, have many poles with the coils connected together. The commutator switches between segments at moments when voltages across the adjacent coils are equal, so there is little sparking. Yes, this is the same as the generator diagram from the last chapter...one of those cases where motor and generator are about the same.

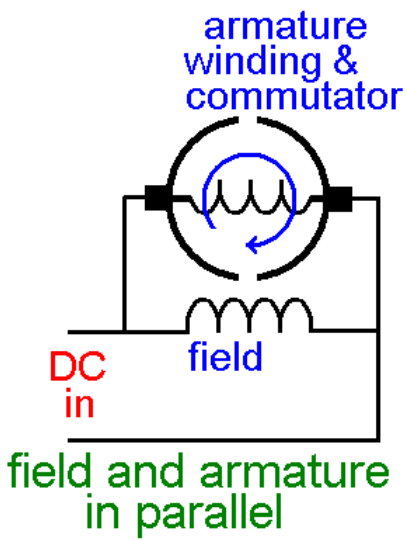


THE SERIES-WOUND DC MOTOR

The illustration above right shows a **series wound** motor, so called because the armature winding and the field winding are connected in series; current flows first through one, then the other.

Series-wound motors are widely used in tools and appliances because they produce the most power for a motor of a given size, and they also have very large starting torque. A series motor has no built-in speed control. If there were no load and no friction, a series motor would spin faster and faster until it destroyed itself. For this reason, series motors are seldom sold by themselves. They are built into a tool or appliance where some kind of load is guaranteed.





THE SHUNT-WOUND DC MOTOR

The diagram to the left shows a **shunt wound** motor. The speed of a shunt-wound motor is more stable than that of a series-wound motor. Since the field winding is not in series with the armature winding, current through it does not vary with load or speed, and the field strength is fairly constant.

Shunt-wound motors don't have especially large starting torque. Again, the shunt-wound motor and generator are essentially the same.

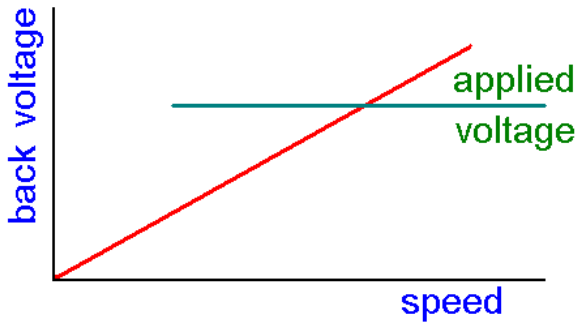
CURRENT LIMITING

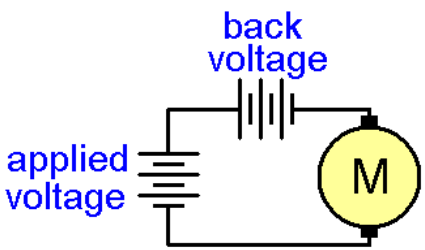
When a motor first starts, in the instant when it's not moving yet, the only limitation on current flow is the resistance of the wire and the inductive reactance of the electromagnetic system. However, once the motor is turning, current is greatly reduced due to the fact that a spinning motor is also a kind of generator.

If you've gone thru the EM3 study guide, you remember the discussion of **back-EMF**. Briefly, if you connect a coil of wire to an DC voltage source, current will flow through the coil and create a magnetic field. But this works the other way too: the increasing magnetic field will induce a voltage in the coil. It happens that the voltage is the same polarity as the source voltage. In effect, the applied voltage is the actual applied voltage minus the back-EMF voltage. This is the reason current flow and magnetic field strength don't go to maximum the instant voltage is applied.

Something a bit like that happens with motors. Applied voltage causes current in the armature, which makes it spin. But the spinning armature, moving within the stator's field, generates a voltage that is the same polarity as the applied voltage.

The faster the motor turns, the higher the back voltage. If the back voltage exceeds the applied voltage, the motor will act as a generator and push current back through the supply. This will put a brake on the motor's rotation, slowing it down until back voltage is less than the applied voltage.





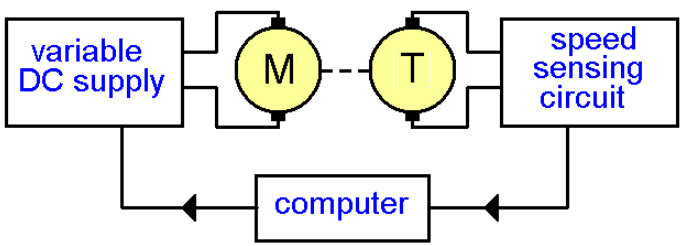
Back voltage acts like a reverse-polarity battery in series with the motor. The net voltage that the motor works on is essentially the applied voltage minus the back voltage.

When a motor is just starting (or if the rotor is prevented from turning, called a **locked rotor** condition), current is normally about six times as high as when the motor is turning at full speed, and sometimes as high as ten times, because there is no back voltage when the motor is not turning, except the small back voltage due to the inductive nature of the armature and coil.

SPEED CONTROL IN A DC MOTOR

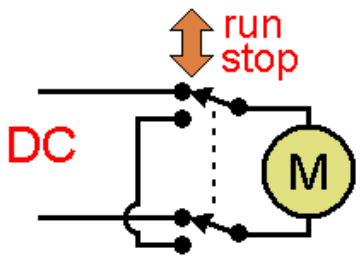
The fact that a motor generates back voltage is the reason a permanent-magnet or shunt-wound motor has a fairly predictable speed. When power is applied, the motor spins up until the back voltage is almost as large as the applied voltage. At that point current is greatly reduced, and the motor will not spin any faster. If we attach a mechanical load to the motor, it will slow down a little and back voltage will be reduced. This is the same as increasing the working voltage across the motor, which prevents the motor from slowing down very much.

This also means that varying the natural speed of a permanent magnet or shunt DC motor is as simple as varying the supply voltage. The motor will speed up or slow down as necessary to generate the right back voltage. A motor that is designed to be controlled in this fashion is called a **servomotor** and it's a basic component of computer-controlled machinery. The elements of a typical servo system are a DC motor, a variable-voltage source to drive it, a speed-sensing device called a **tachometer** to detect how fast it's going, and, nowadays, a computer to control the process.



A series-wound motor doesn't have this built-in speed control because, as the motor turns faster, the strength of the magnetic field changes so less back voltage is generated. The speed of a series-wound motor varies with applied voltage, but in a less predictable manner.

BRAKING A DC MOTOR



If you have to stop a DC motor quickly, there's a lot to be said for doing it electrically rather than using friction pads. Pads wear out and go out of adjustment. But, if a motor generates back voltage, stopping it quickly is as easy as putting a resistor or short across it. This is a very stable braking system, especially if there's a tach and computer to monitor what's going on.

If you just want a quick brake, you don't need any monitoring circuitry. I have a chop saw that throws a short across the motor to brake it when I release the handle. Great safety feature.

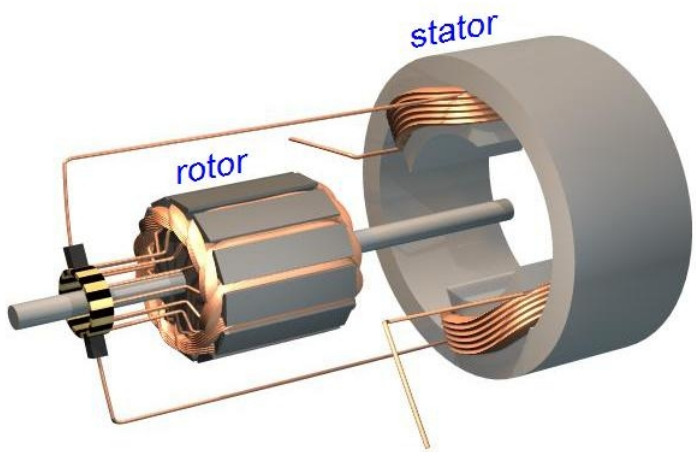
UNIVERSAL MOTORS

Let's return to the series-wound motor. What would happen if you reversed the DC voltage? A lot of people would guess that the motor would reverse directions, but a lot of people would be wrong. True, the current would flow the other way in the stator, and its polarization would flip. But it would also flow the other way through the brushes, so the rotor polarization would flip as well. In the end, the motor would run the same direction as it did before.

If this is true – if voltage polarity doesn't matter with this kind of motor – then, obviously, it will also work with AC. This is called a **universal motor** because it runs on any kind of current. That came in handy during the time when the grid was converting from DC to AC, which took decades. The first buildings were wired for AC early in the 20th century, but some old buildings still had DC outlets into the 1970s. (Some buildings in California are still partially supplied with DC.) For a long time, when you brought a new appliance home and plugged it in, you never knew whether it was going to blow up. But universal motors always worked.

The grid is all-AC now, but universal motors are still built by the millions because they have several other advantages.

- they've been made for more than a century, so there are no problems left to solve. Factories are already set up to bang them out like bottle caps.
- series-wound motors can easily be made to run faster than the AC power-line frequency, typically 10,000 to 25,000 RPM. A fast motor can be geared down to produce a lot of torque in a small package.
- they develop more power for their size than any other kind of motor, and they have huge starting torque.



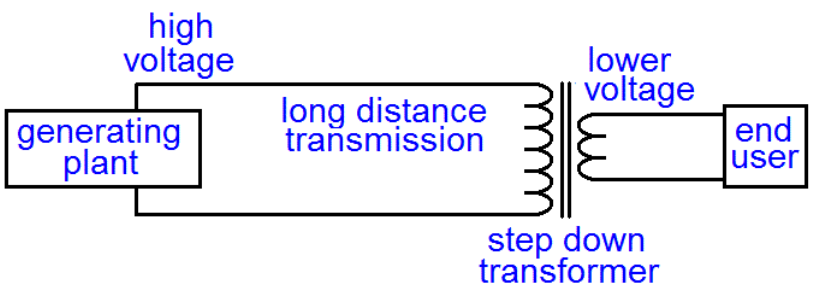
The illustration above is an exploded view; in an actual motor the rotor would of course be inside the stator.

(After I did the illustration, it occurred to me: hey, those coils look like bare copper! The plastic “varnish” on magnet wire is often transparent, so it looks like bare wire. Just so we're clear: the wire is insulated, it would be useless if it weren't.)

Universal motors are used in vacuum cleaners, AC-powered hand tools, egg beaters and similar applications where speed control isn't critical and the motor won't have to run for long periods at a time.

AC MOTORS

The USA was well along the way to being completely wired for DC before AC came along. Why did the country convert its grid to AC? One reason was that AC voltages can be changed using transformers. This permits a lot of power to be transmitted at a high voltage over a long distance, and then stepped down to a usable voltage at the end point. Our modern power grid wouldn't be possible without the ability to do that. If you've gone thru the EM2 study guide, you know transformers only work with AC.



Nikola Tesla promoted AC partly for this reason, but he wasn't the first to see that benefit. What Tesla was first to see was how AC could be used to make a motor without the need to pass all the current through brushes.

In a factory, we might find motors the size of houses, and in the DC days they all had brushes. Think how much crud they would shed and how much maintenance they required.

The story goes that Nikola Tesla was looking at a sunset one evening and the inspiration for the AC motor came to him in a flash. He saw it so clearly that he actually reached out, flipped an imaginary switch, and visualized it turning into a generator. With the invention of the AC motor, Tesla had everything he needed for a superior power system: a way to transmit power long distances, an easy way to change one voltage to another, and reliable, low-maintenance motors.

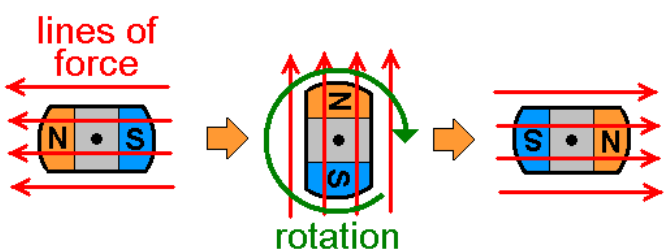
AC MOTORS AND 3-PHASE POWER

You remember from chapter 3 that power plants generate 3-phase power, consisting of three sine waves 120 degrees apart. Now I'm going to show you why.

The AC motors Tesla invented are multiple-phase or **polyphase** motors. From an engineering standpoint, a polyphase motor is the "natural" kind of motor. Most of the motors we actually deal with every day are single-phase motors, but those came later.

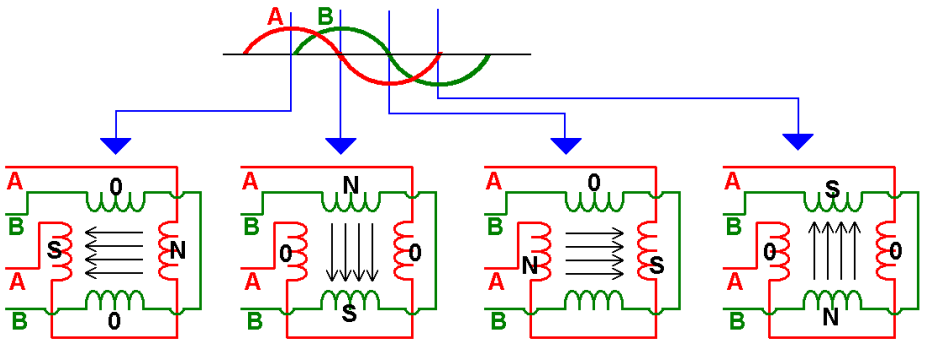
The key to the polyphase AC motor is a concept that is ridiculous at first glance: a **rotating stator field**. "Stator" implies "stationary." You might ask, especially if I give you an obvious nudge like this, how can a stationary stator's field rotate? How smart of you to think of that.

First let's recognize that *if* we can actually get that to happen, we can make a brush-free motor. If we take a permanent-magnet rotor and place it in a magnetic field, it will align itself with the field like a compass. Once it's aligned, it won't move. However, if we can make the field rotate, the rotor will rotate along with it.



So, how might a rotating field be created? We could mount the stator on bearings and spin it around. But we'd need a motor to spin it, so we haven't gotten anywhere.

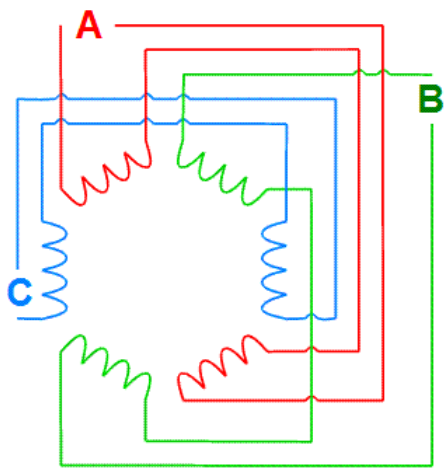
Enter Tesla. Suppose we create two sine waves, 90 degrees apart. Notice: whenever one sine wave is at a peak or valley, the other is at zero.



Suppose we build a motor with two sets of stator magnets, 90 degrees apart, four poles total, and connect the windings on the left and right poles to sine wave "A" and the winding on the upper and lower poles to sine wave "B." Pole magnetization will be the same as sine wave voltage: whenever one set of poles is magnetized, the other isn't. In the illustration above, the blue arrows represent "snapshots" taken when waveform B is at 0 degrees, 90 degrees, 180 degrees and 270 degrees. The black arrows represent magnetic lines of force.

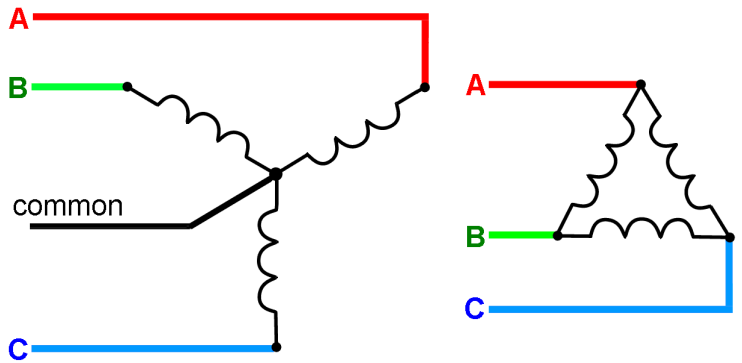
Note that as the sine waves progress through one cycle, the lines of force progress through one rotation, counterclockwise in this case. That, Meine Damen und Herren, is a rotating field. If we put a magnetized rotor in it, it will rotate too.

Tesla's early AC motors were 2-phase motors, but it was soon discovered that there are advantages to basing generators and motors on three phases, 120 degrees apart. This means 3-phase motors need to have three pairs of stator poles.



Tesla's invention of the rotating-field motor was so valuable that it allowed Tesla's friend and financial backer, George Westinghouse, to build a giant company in direct competition with Edison's well-established General Electric. (Westinghouse was an inventor in his own right – he invented railroad air brakes among other things.) Today, all large generators and the nation's entire electrical grid provide 3-phase power, because all large motors are 3-phase motors.

3-phase motors can be made in a wye configuration or delta configuration, depending on what works best for the application.



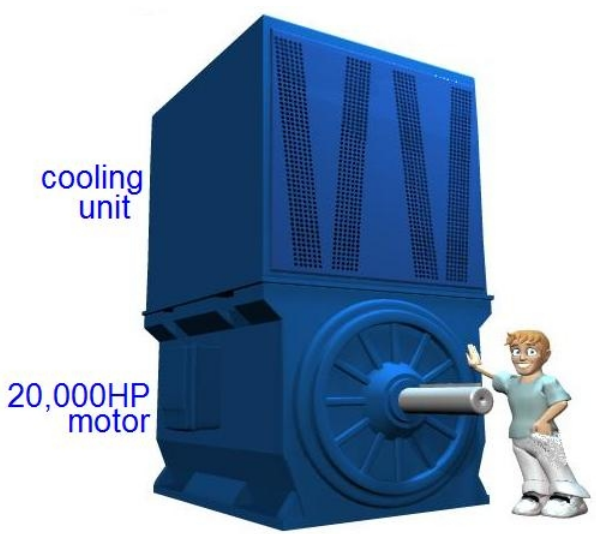
SYNCHRONOUS MOTORS

With a DC motor, speed can be anything, depending on how it's built and what voltage it's running on. With an AC motor, speed is controlled by how fast the field is rotating, which is controlled by the AC line frequency.

When the rotor is a permanent magnet, rotation of the armature will keep exactly in step with the rotating magnetic field. If the field frequency is 60Hz, a 6-pole, 3-phase motor will turn at exactly 60 revolutions per second, 3,600 revolutions per minute. This is called a **synchronous** motor.

One early adopter of the synchronous motor was a gentleman named Laurens Hammond. It occurred to him that if power companies could be persuaded to run their AC generators at exactly 60Hz, then people could have clocks that would always keep perfect time and never need to be reset, except after power outages. Hammond essentially invented the synchronous clock, and motor-driven clocks use his design to this day. (Today, the average digital clock either gains or loses time and must be reset every once in a while. This is actually a step backwards. Fifty years ago, clocks kept perfect time.) Looking for another use for the synchronous motor, Mr. Hammond invented the Hammond organ.

Large permanent magnets are expensive, so large synchronous motor rotors are usually electromagnets, powered via slip rings. We're back to brushes – but comparatively small ones that only handle rotor magnetizing current, not the current that actually turns the rotor.



The very largest motors are often synchronous, not because it's important to have exactly 3,600RPM, but because the best synchronous motors are very efficient. When a motor is consuming megawatts, any waste is a big waste.

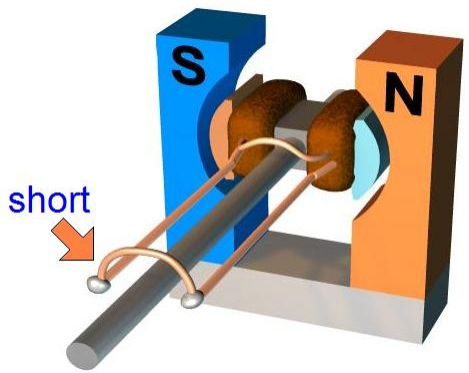
There is a way to make a synchronous motor with an unmagnetized rotor, and that is to cut slots in it or make it in a shape which “cogs” or catches on the rotating field. You can't get much torque out of this kind of motor; if you try it will just stop. But it is used successfully for such things as motors in mechanical clocks, where the load on the motor is very light.

INDUCTION MOTORS

In things like saws, pumps, fans and in fact most things, it doesn't matter if the motor turns at a synchronous speed or not. In those applications, we don't need an expensive, permanently magnetized rotor or one electrically magnetized via slip rings. Instead, we just let the field magnetize the rotor through magnetic induction, which we studied in EM1. This is called an **induction** motor, because the field in the rotor is induced by the field in the stator.

Think about a generator with the armature winding on the rotor, spinning a stationary field. The field creates a voltage in the spinning winding. If we attach an electrical load to the winding, current will flow – and you know current flowing in a winding creates its own field. Lenz' law states that this field will work against the original field, making the generator harder to turn.

What do you suppose will happen if we short the wires? Suppose, in fact, that we eliminated the commutator or slip rings and short the wires right at the rotor? It would suddenly become very hard to turn the rotor at all, relative to the stationary field. In fact, this technique is used to create electromagnetic brakes.



But what if the field is *not* stationary? What if it's being created by 3-phase power, and it's rotating? The rotor lives in this field, and all it knows is that it wants to remain stationary *relative to the field*. It does not know that this field is rotating!

When you stand in one place, it seems you're standing still, but you know you're really not – the Earth is spinning and you're moving with it. On the other hand, if you got in a very fast plane and flew West at the same speed as the Earth's rotation, you would then actually be standing still relative to the Earth – but to you, looking down at the Earth, it would seem like you're moving.

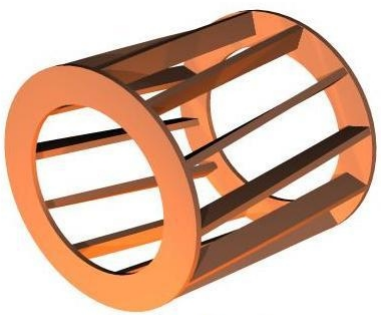
To the rotor, that's what life in the rotating field looks like. From the rotor's viewpoint, “stationary” means spinning at the same speed as the field. So, as the field rotates, it drags the rotor around with it. Voila! – a motor. With an induced rotor magnet and a shorted winding, we no longer need any electrical connection to the rotor at all. That means the brushes and all their problems go bye-bye.

SLIP

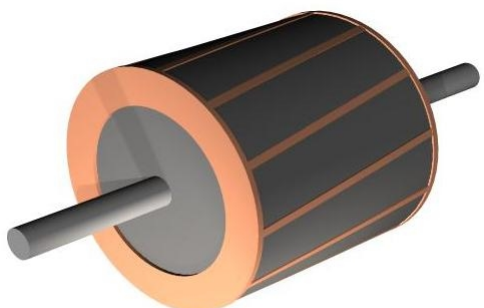
It's important to note that, if the rotor actually turned at exactly 3,600 RPM, no voltage would be induced in the shorted rotor winding, thus no current would flow in it, thus no Lenz'-law torque would be created. An induction motor must run a little slower than synchronous speed, because it's that small difference that causes the rotating magnetic field to cut across the shorted rotor winding, generating the current that creates the torque. The speed difference is called **slip**.

When the motor is not loaded, it takes very little slip to induce enough current in the rotor to keep it turning – perhaps one lost revolution every couple of seconds, or a speed of 3,599.5 RPM. When a motor is carrying the maximum load it is designed for, the slip is usually on the order of 3-4%, which is to say the full-load motor speed is around 3,500 RPM.

The simplest way to create a good shorted winding is to cut slots in the rotor, push in heavy copper bars, and weld the ends to copper plates. This creates a very low-resistance copper structure that resembles a squirrel cage. This is kind of motor is called a **squirrel-cage** motor, surprise surprise. If you pull the rotor out of an induction motor, the right-hand illustration below is what you will see.



copper squirrel cage



squirrel cage and rotor

Note that even in this case, eddy currents must be prevented, so the rotor is laminated. If we let eddy currents occur, they would flow in directions that don't generate torque, and simply soak up power. Note also that the copper shorting bars are angled, for the same reason gear teeth are often angled: to improve the smoothness of rotation.

Review so far: a rotor that is a permanent magnet, or an electromagnet, or an induced magnet with a shorted squirrel cage, will not want to rotate relative to the field. We make it rotate by making the field rotate. We create a rotating field by feeding several electrical phases, spaced apart in time, to several field poles, spaced apart by angle.

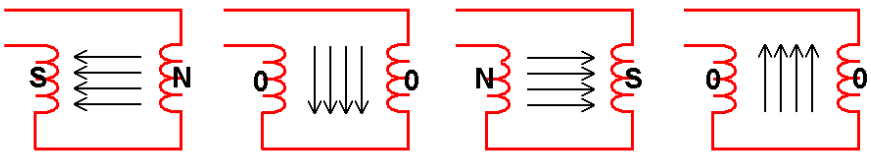
SINGLE PHASE AC MOTORS

We've come to the point in the development in the U.S. electrical industry where we've got everything we need to create large amounts of 3-phase power, deliver it to, say, a large factory, and use it to run large 3-phase motors.

But we haven't provided for small users, like homes and small businesses. These buildings are wired with two wires, a hot supply wire and a white return wire (plus a green safety ground wire), which is to say **single phase** power. And why not: a lamp, toaster or universal motor does not need three phases any more than it needs AC.

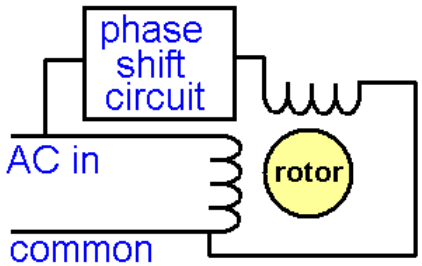
But we really would like to get rid of those motor brushes. It's one thing to have brushes in a motor that doesn't run much of the time, as in table saws and hand drills and vacuum cleaners and kitchen mixers. It's another thing to have brushes in, say, a window fan that runs all day. There, brushes will wear out. How can we make a brushless induction motor work on a single phase?

If you get a 3-phase motor up to speed and then switch it to single-phase power, it will keep running. Magnetic induction has magnetized the rotor, and it's spinning at nearly 3,600 RPM, so the rotor's magnetic poles come around to the two remaining magnetized stator poles just about when they should, 120 times a second. Between those times, the rotor's momentum keeps it going.

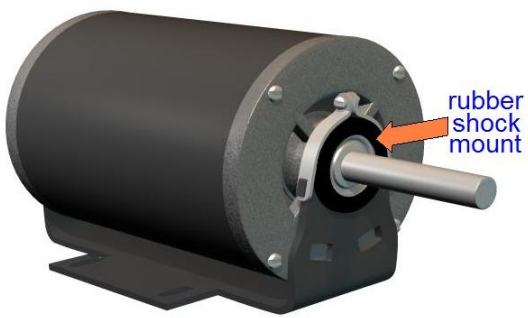


Thus the problem of running an AC motor on a single phase comes down to how to start it. The way it's done is by **splitting** the single phase right inside the motor, which means deriving a second sine wave that's 90 or so degrees out of phase with the power coming in. In other words, a single-phase motor is really a 2-phase motor with a rotating field, at least during start-up.

It's a strange fact: the electrically “normal” AC motor is a 3-phase motor, but most people never come in contact with it. On the other hand, the single-phase motors that everybody actually uses – in refrigerators, washing machines, fans and other appliances – do not make use of the three available phases. They must have some kind of built-in phase-splitting mechanism to manufacture a second phase, so they can work in an electrical environment that wasn't designed for them, like a diver who must carry an air tank to breathe underwater.



A single-phase motor must be larger than an equivalent 3-phase motor. Also, there's often a small torque pulsation, an undesirable vibration that can be transferred to the load. Some single-phase motors are mounted on rubber rings to reduce this effect.



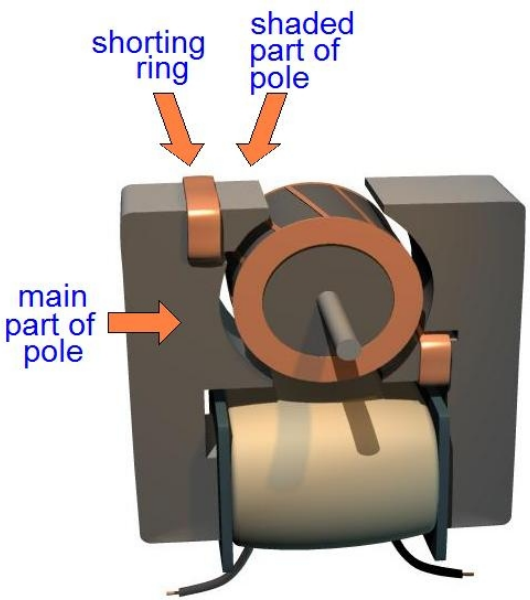
Single phase AC motors come in two flavors:

- motors which use the second phase to run all the time
- motors which use the second phase until they're up to speed, then switch it off

A single-phase, 3,600 RPM (or almost 3,600 RPM) motor is usually called a **2-pole** motor, which is not entirely accurate. The motor needs two other poles for that second phase, even if they're smaller and weaker and only used during starting.

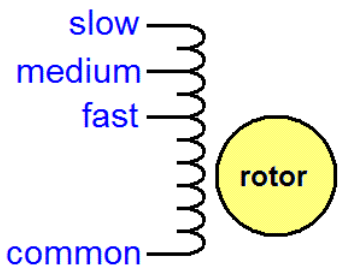
THE SHADED POLE MOTOR

The simplest way to turn one phase into two is with a **shaded pole** motor. Each of the stator poles is split, and part of each pole is encircled by a copper ring. This amounts to a shorted transformer turn. In the illustration, the bearing assemblies have been removed so you can see the poles and shorting rings.



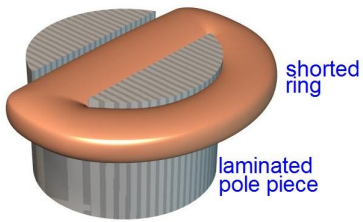
This could be called a “sorta-4-pole” motor. The high current induced in the rings shifts the phase of the magnetic field in that part of the poles so it's delayed relative to the main pole. We get a weak and crude, but adequate, rotating field. Window fans typically use this kind of motor. The shorted copper rings mean there's always some power wasted (and they get hot – don't touch them!), but for low-power motors that's not a big deal.

Shaded pole motors usually have so much slip that the usual rule doesn't apply: they don't necessarily turn at anything near synchronous speed. If there's a load on the motor, and you reduce the voltage, it will slow down. We can do this another way by adding more turns of wire in the coil, which has the same effect as reducing voltage. If we tap the coil at several points, we can have several speeds. That's how a 3-speed window fan works.

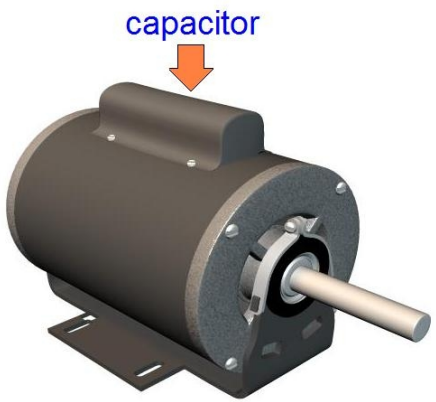


Side note – now I can explain something I told you back in EM3: an AC relay pole piece is usually split, with a copper ring around half.

The magnetization of a pole piece running on AC will be zero twice each cycle. That means, 120 times a second, the armature will begin to move away from the pole piece and then get smacked down again. This will create a loud buzz – that's how AC buzzers are made. But what if we don't want the buzz? Well, if the pole is split and half of it is shaded with a shorting ring, that creates two magnetic phases, meaning some part of the pole piece is always magnetized, and the armature is always held down. Buzz gone. If you look at a relay and see a split pole piece with a shorting ring, it's an AC coil.

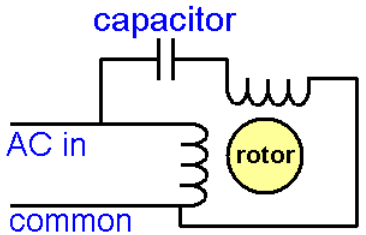


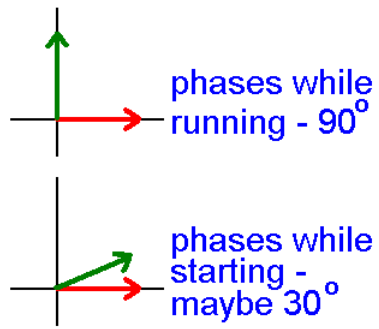
THE CAPACITOR-RUN MOTOR



Another way to get a rotating field is to employ our old friend, the capacitor. If we create a second set of stator poles offset by 90 degrees from the main set, and feed their coils through a capacitor of the right size, we'll get a 90-degree electrical phase shift and a rotating field. This is called a **capacitor-run motor**. If you see a cylindrical bump on top of a motor, that's a capacitor.

A problem with a capacitor-run motor is that it has low starting torque, and if the load is massive, it can take a long time to get up to speed. This is because the magnetic behavior of the motor is much different when starting than when running, so the inductance of the windings is much lower when starting than when the motor is at full speed. As a result, the phase shift developed by the capacitor and associated winding is nowhere near 90 degrees during starting. Since that phase shift is what creates the rotating magnetic field, you can see why a smaller phase shift would reduce starting torque.

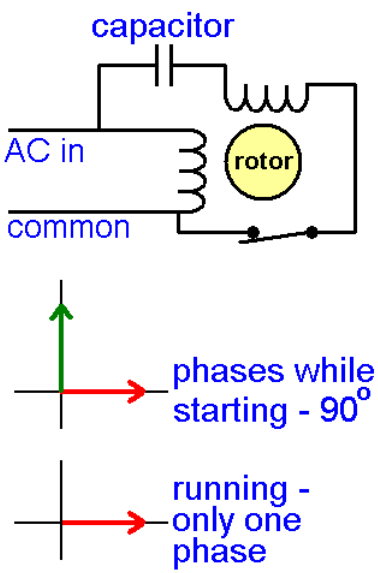




THE CAPACITOR-START MOTOR

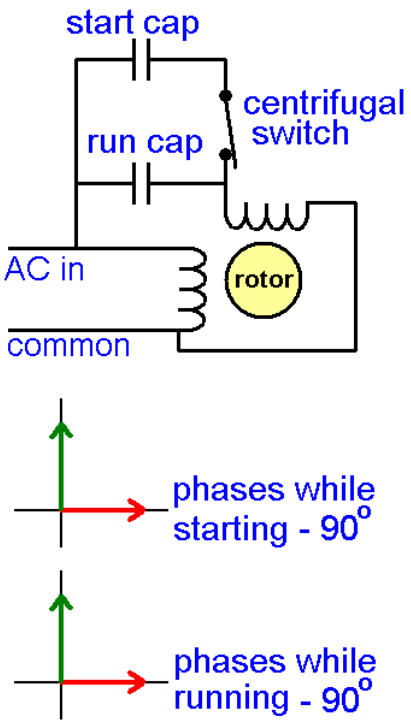
Another problem with a capacitor-run motor is that it is constantly putting high AC current through the capacitor, which can heat it up and dry out the liquid that fills it.

But we luck out here. Recall that, once a motor is up to speed, it no longer needs the rotating field. All we have to do is connect a capacitor to the second winding long enough to get it up to speed. Then a switch in series with the capacitor can be opened, taking it and the second coil out of the circuit. This is called a **capacitor-start motor**. The capacitor-disconnecting duty is typically handled by a centrifugal switch spun by the rotor that is **thrown out** when the motor reaches full speed.



Since the capacitor is only in the circuit when starting, we can choose a capacitor that will create an actual 90-degree phase shift. This tremendously increases starting torque. The capacitor is likely to last longer than the one in a capacitor-run motor, since it's not used most of the time. The disadvantage is that the 90-degree winding is not in the circuit when the motor is running, so it has less torque than a capacitor-run motor of the same size. Also, the centrifugal switch can malfunction. I've got a big belt sander I can't use right now because the centrifugal switch doesn't work. The starting winding stays in the circuit all the time and the motor overheats in about ten seconds.

THE CAPACITOR START AND RUN MOTOR

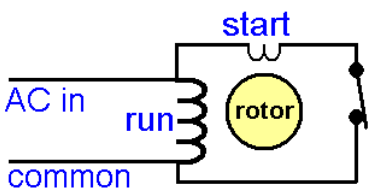


We can have the best of both worlds by using a large capacitor to create starting torque, and a smaller capacitor that stays in the circuit when the motor is up to speed. A motor with two bumps on top is a capacitor start and run motor.

A few years ago, I installed a capacitor-run blower that took a full half minute to get up to speed. I added a capacitor-start circuit, turning it into a capacitor start-and-run motor. That reduced starting time to four seconds. The benefit is obvious: this kind of motor has high starting torque and high run torque. The disadvantage is that it's more complicated, so there's more to go wrong, and it's more expensive.

SPLIT PHASE MOTOR

All single-phase motors use split-phasing at least to start, but the motor that is normally called a **split-phase motor** is like a capacitor-start motor with no capacitor. The run winding and the start winding are connected in parallel, with a centrifugal switch to disconnect the start winding when the motor gets near full speed.



The split-phase motor relies on differing winding reactances. If you've done the EM3 study guide, you know reactance is the AC resistance-like characteristic of a coil of wire, which is caused by the varying magnetic field. In a split-phase motor, the run winding consists of many turns of heavy wire. The start winding consists of fewer turns of fine wire. The run winding is more inductive and the start winding is more resistive, which causes current in the run winding to lag current in the start winding.

This results in a phase difference, but nowhere near 90 degrees. It's enough to get the motor started, but starting torque is low. For this reason, large split-phase motors are rare. The advantage is that we can eliminate the expensive and often troublesome capacitor.

When counting poles in a single phase motor, only the main running poles are counted. A 3,600RPM single-phase motor is always considered a 2-pole motor.

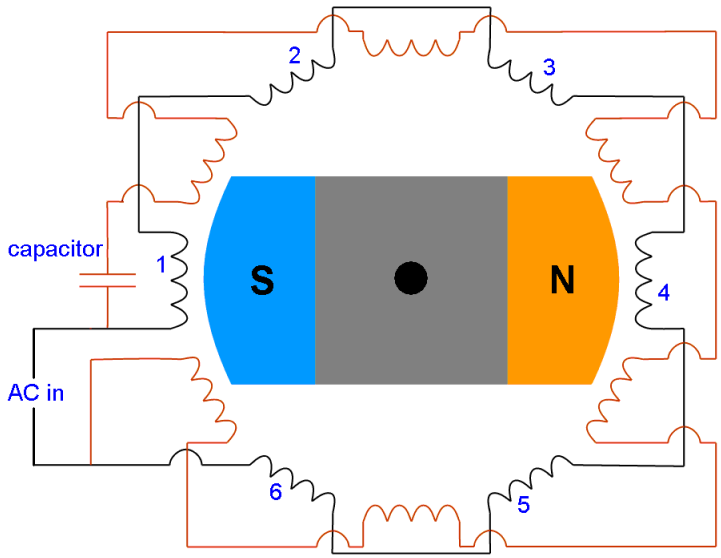
MORE POLES, LOWER SPEED

The motors we've studied so far are either 6-pole 3-phase motors or 2-pole 1-phase motors, having one pair of poles per phase. In each case, speed is 3,600RPM for a synchronous motor or 3,600 minus slip for an induction motor.

But, like a generator, a motor can be built with several pairs of poles for each phase. At 60Hz, synchronous speed is 7,200RPM divided by the number of poles. A single-phase, 4-pole synchronous motor runs at 1,800RPM, a 6-pole motor runs at 1,200RPM and so on. Sometimes, for special purposes, an AC motor is built with a whole lot of poles to obtain even slower speeds.

A synchronous 6-pole capacitor-run motor is shown on the next page. The main poles are black; these are the ones we count. The out-of-phase poles are red. If this were a capacitor-start motor, there would be a switch that disconnects the red poles when the motor gets up to speed.

In a 2-pole motor, the rotor would make half a turn in half a cycle. In a 6-pole motor, it only gets as far as the next black coil. Thus the speed is 1/3 x 3,600RPM, or 1,200RPM.



POWER LEVEL

Rotary mechanical power is **speed times torque**. Speed is measured in RPM. Torque is usually measured in foot-pounds.

A more common way of measuring a motor's power is in **horsepower**. Back in EM1, we talked about the fact that one form of energy can change into another form of energy.

Mechanically, one HP is the ability to do 550 foot-pounds per second of work. That is, it takes 1HP to lift a 550lb load one foot in one second. If we need to do some other kind of work, an engineer would use mechanical laws to convert to foot-pounds.

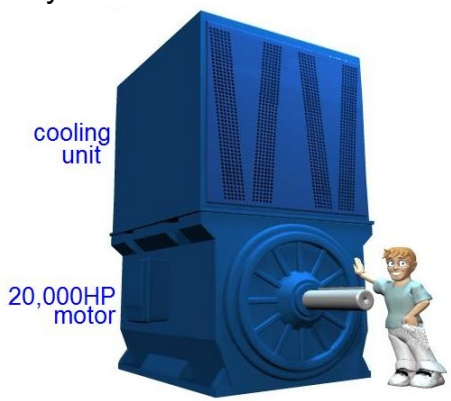
HP can also be measured electrically: **1HP = about 746 watts**. If you put 746 watts into a 100% efficient 1HP motor, 550 foot-pounds of work would come out every second.

EFFICIENCY

When the motor is operating normally, the current draw is a lot like current draw in a transformer: current is proportional to load. Unlike transformers, when there is no load, current draw is still substantial.

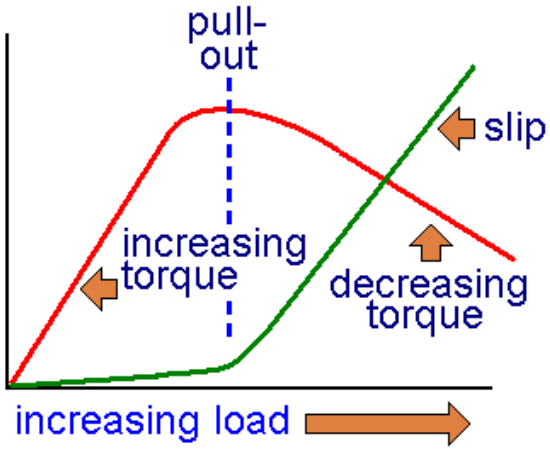
Most motors are ridiculously inefficient compared to transformers. An unloaded motor will still draw up to 40% of its full-load current. At full load, efficiency may be only 70%. “High efficiency” motors achieve 80%. That means an average motor creates 1 watt of waste heat for every 2 watts of mechanical output, and a high efficiency motor creates 1 watt of heat for every 4 watts of output. No wonder so many motors have built-in fans! A 1HP motor typically requires about 1,100 electrical watts of input.

It's always been possible to build more-efficient motors, but the initial cost is so high that it takes years to recoup from savings in electricity. However, when we get to monster motors, that kind of power waste is not acceptable – not only because of the cost of electricity, but how would you get rid of that much heat? That 20,000HP one I showed you is over 97% efficient, and even at that the ventilator is bigger than the motor. (Bet you're wondering what one of those costs. Upwards of a million bucks. Will that be cash or check?)



OVERLOAD AND PULLOUT

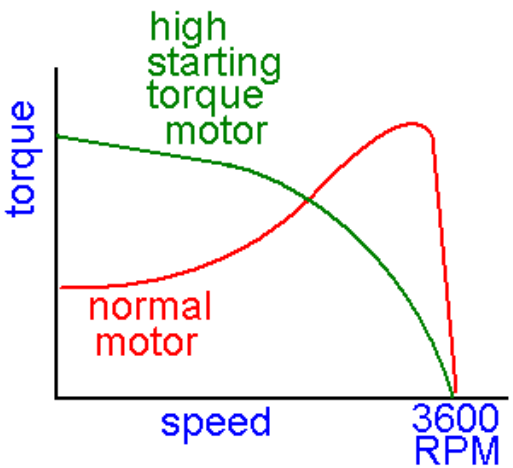
We've seen that, for an AC induction motor, the greater the load, the more torque it must produce, and the more it slows down – that is, the greater the slip. If we graph torque vs. slip, we can see this happening at speeds near 3,600RPM (or 1,800 or whatever, depending on number of poles). However, if we increase the load enough, an interesting thing happens: the slower the motor turns, the *less* torque it produces.



When the motor gets into this region of the torque curve, slip is so great that magnetization in the rotor varies wildly and no longer bears any relation to the rotating field. This is a condition known as **pullout** – the motor pulls out of synchronization or almost-synchronization with the AC power frequency. Once past the point of pullout, the more the motor slows, the less torque it produces, slowing it even more. When the motor sees that it's fighting a battle it can't win, it gives up and grinds to a halt.

One common case where stall torque is lower than running torque is a refrigerator or air conditioner compressor. When it's running, it pumps up a lot of pressure. It can continue to run against this pressure, but it can't start against it. That's why, if you stop an air conditioner and then immediately start it again, it just buzzes and the thermal breaker clicks in and out. It takes a while for the pressure to dissipate so the motor can start.

Motors that must start with a heavy load are made with a special speed/torque curve which trades greater slip for high starting torque. Or, series-wound universal motors are used, which have both good efficiency and extremely high starting torque.

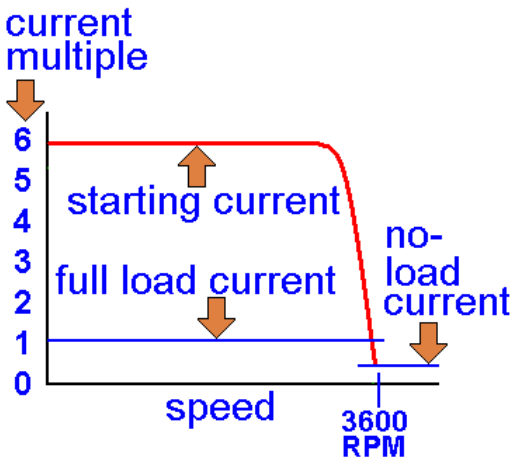


START / STALL CURRENT

When an AC motor is turning, it acts as a generator, creating a kind of back-voltage-on-steroids that limits current. This is the same effect mentioned earlier in connection with DC motors. When the motor is just starting up this generated voltage is absent. This also happens if you overload the motor and stall it. In that case you only have inductive back-EMF and wire resistance to limit current.

The graph to the right above shows speed vs. current for an induction motor. “Current multiple” means how much current is flowing at a given speed, compared to normal current when the motor is at full speed and fully loaded.

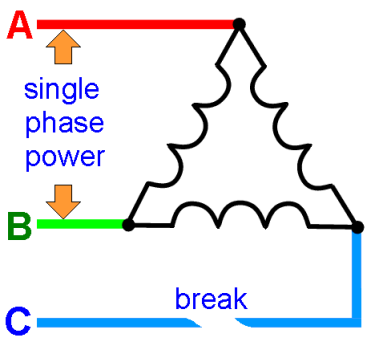
When the motor is starting, it draws about six times the full-load current until it gets almost up to full speed. (Some motors draw up to ten times full-load current.) The only reason this doesn't burn the motor out is that it usually only takes the motor a second or so to get up to speed. If the motor stalls, creating a long-lasting overload, the breaker trips. If there's no breaker, the motor burns up.



If there is no load on the motor, current is about 40% of full-load current, and speed goes up to almost 3,600RPM.

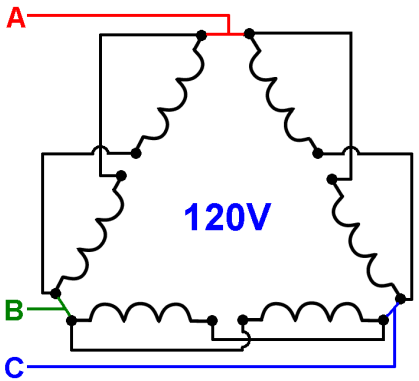
An exception to the six-times rule is the small **impedance protected** motor that can be stalled without overheating. Most shaded pole motors are impedance protected.

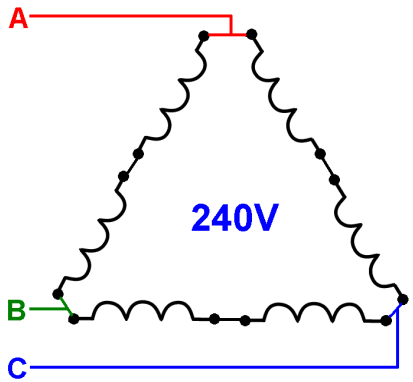
There's a situation where breaker protection may not work. With a 3-phase motor, one of the most frequent causes of motor burnout is one of the electrical phases disappearing due to a broken wire or some other fault. This leaves the motor connected across two “hot” wires, essentially a single-phase system. If the motor is running, it may continue to run, but if it's stopped, it won't start. However, with a phase missing, we won't get the full 600% stall current, and the breaker may not trip. If this keeps up, the motor will burn out. And we can't just use a smaller breaker, or it will trip in normal operation. This is called **single-phasing**, and in 3-phase systems, this problem just goes with the territory.



MULTI-VOLTAGE AC MOTORS

A manufacturer can sell a lot more of a particular motor if it can run on several different voltages. When we studied transformers in EM3, we saw that a winding can be split in half. This can also be done with motors. When the windings are connected in parallel, the motor runs on one voltage. When they're connected in series, it runs on a different, higher voltage.





In the left-hand diagram above, look closely – the two halves of each phase are connected in parallel. In the right-hand diagram, they're connected in series. The voltage across each half of each winding is 120V in either case.

Is it that important to get the voltage right? Yes! Many AC motors get unhappy if the supplied voltage is more than 5% over or 10% under the specified voltage.

Speaking of voltages, I've been blithely assuming motors are designed for 120V or 240V. Many motors are specified for 115V or 230V. This is a leftover part of the historic disagreement over exactly what the standard U.S. voltage should be. Some countries have all-powerful governments that decide these things, which makes things simpler but tends to stifle innovation.

In the USA, the people who actually make motors, generators, light bulbs etc decide them, which is usually (not always) better for technical progress but does lead to situations where the right hand doesn't know what the left hand is doing. Electronic equipment manufacturers often split the difference and specify 117V for their stuff. This is not really a big issue. The difference between 115V and 120V is about 4%, well within the motor's “comfort zone.”

Some motors run on 208V. Where'd that strange number come from? Well, I'll tell ya – in the next chapter.

SPEED CONTROL OF AC MOTORS

One of the most annoying problems of AC motors has always been that, with the exception of universal motors, it's difficult to control their speed. The speed of an AC motor is determined not by the voltage but by the line frequency. Most AC motors are built to run on one voltage (or a choice of voltages, if it has split windings) and at one speed, and that's it.

In the past, there have been three main ways to solve this problem:

- Use a big DC motor with a big variable-voltage DC power supply. In the days before switching power supplies, this involved some heroic engineering and a huge amount of power burned up as heat.
- Use a high-slip AC motor and vary the voltage with an autotransformer. This works well when the load is constant, but if the load changes, the speed changes.
- Let an AC motor run at a single speed and use belts and gears to change to a different speed. There's a way of making pulleys into a continuously-adjustable speed mechanism, but it loses a lot of energy to friction. Machinists tell me their old variable-speed vertical mills used to lose almost 50% of the horsepower between the motor and the output.

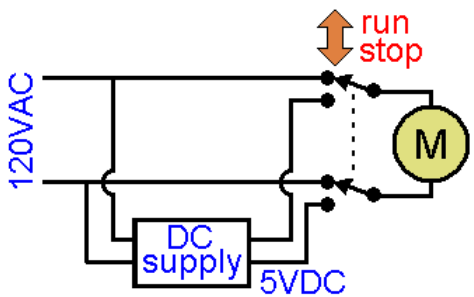
If your career path takes you into machine control, you may very well run into these methods in older equipment. Industrial machines are too expensive to discard every time something new comes along. I'd be surprised if you didn't have to work on stuff that's older than you are.

But in new machinery, these methods have been replaced by the **variable speed drive** or **VFD**. Inexpensive, high-power solid state components now make it possible to take 60Hz AC, rectify it to DC, then turn the DC into AC at some other frequency. A VFD capable of handling a 1HP motor can be bought for under $200.

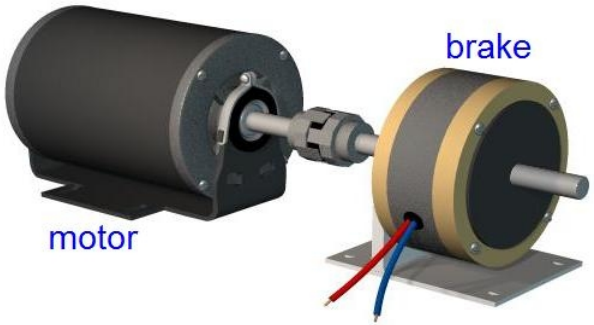
AC MOTOR BRAKING

I mentioned that a DC or universal motor can be quickly stopped by shorting its leads. An AC motor can be braked using a different but related method.

In an induction motor, the rotor does not like to turn relative to the stator's field. What would happen if we put a DC voltage on the stator winding, so as to create a stationary field? The rotor would not turn, and it would resist being turned by an outside force, as if the motor were full of heavy axle grease. This is how a **dynamic brake** is made.



An induction motor can be made to both run and brake, by switching its field winding between AC and DC. On DC, the voltage has to be very much lower – maybe 5V for a 120VAC motor – because there's no back-voltage to limit current. It's best to check with the manufacturer to verify that this use won't cause, for example, permanent magnetization of the poles.

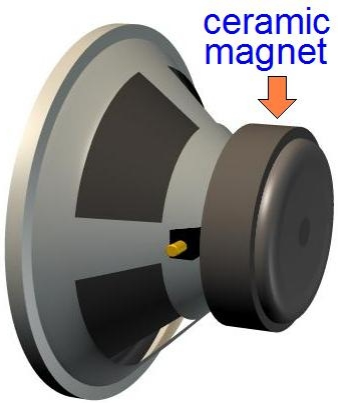


More often, a separate unit that's designed for the purpose is used for braking. Dynamic brakes are widely used in things like packaging equipment, or anywhere a machine has to start and stop all the time. Their advantage is that they don't have brake pads to wear out, and they don't go out of adjustment. They can stop hundreds of thousands of times with no change in their characteristics. Their disadvantage is that, if power fails unexpectedly, you could find yourself with an out-of-control machine and no way to stop it. For this reason, regular friction-type brakes are usually provided as a backup.

At this point you've got a good handle on traditional motor technology as it's been used since the beginning of the 20th century. As I said in the previous chapter, most modern motor technology is just old motors with new solid-state control systems. But electronic control has also made a few new motor types possible.

BRUSHLESS DC MOTORS

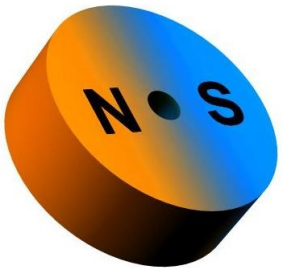
There's no actual law that says DC motors must have brushes, only that they must have commutators. With today's efficient, high-power switching transistors, we can build electronic commutators.



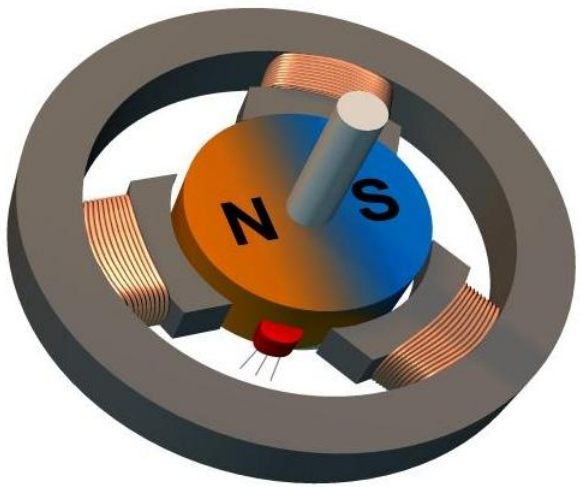
We need to take a moment to talk about the **ceramic magnet**, which is a ceramic material with a lot of ferromagnetic particles mixed in. The ceramic material starts as a goo that resembles library paste. It is pushed into a mold and allowed to harden. (One of the reasons ceramic magnets are so popular is that they can be molded in any shape.) Then the magnet is "charged," that is, magnetized. Ceramic magnets are usually black. If you look at the back of a speaker, you will usually see a black ring. That's a ceramic magnet.

When the magnet is charged, the magnetization can be in almost any pattern. It's possible to put poles about anywhere they need to go, as long as the rule is observed that poles come in pairs, and every North pole must have an opposite South pole.

Let's take a ceramic donut and charge it with one pair of poles. It's still black, but if you could see the magnetism, it would look like this.



Now let's put a shaft through the middle and put the magnetized donut near three coils of wire. Let's provide a circuit that drives those coils with 3-phase power. You remember the toy motor with two permanent-magnet field poles and three rotating armature poles? This is the same thing, except the field and armature have traded places. The field is the rotor and the armature is the stator – I know, that doesn't seem right, but it is. Electronic circuitry switches voltage to the coils at the right moments to keep the rotor spinning. Since there is no electrical contact with the rotor, there's no need for brushes.



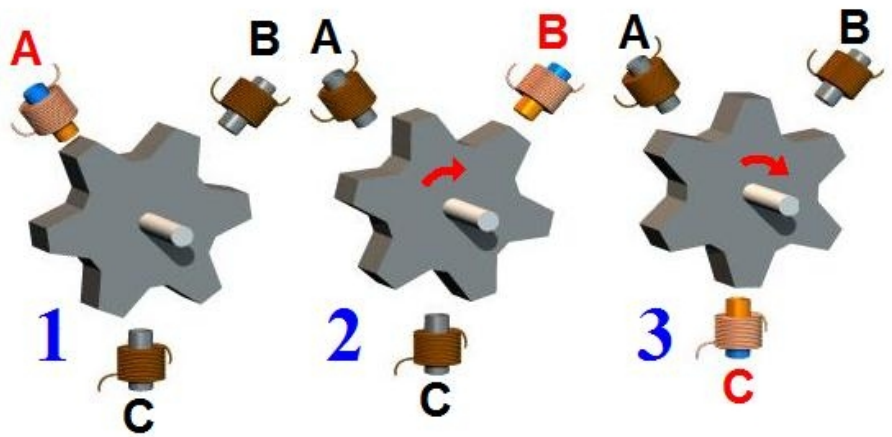
So, how does the 3-phase drive circuit know when to switch? Well, we put a magnetic sensor near the rotor, and it senses the position of the rotor and tells the drive circuit when to switch the coils. The sensor is usually black, but I've made it red in the illustration so it's easier to see.

Anybody who has been around computers has seen "pancake" vent fans like this one. A few of these run on 120VAC and use induction motors, but the rest, pretty much without exception, use brushless DC motors.

STEPPER MOTORS

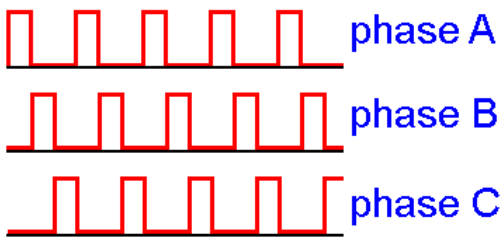
We've seen that electricity can be used to stop a motor as well as run it. But electrical braking doesn't stop a motor *at a specific position*. A shorted DC motor, or direct current through an AC motor, will create a Lenz-law force that makes the rotor hard to turn, but won't lock it. There are a huge number of cases where a motor must move a machine to a certain point and then stop precisely at that point. That's what a **stepper motor** is for.

The illustration below is simplified, meant to illustrate the concept more than to represent an actual motor. To begin with, note that the rotor has teeth. These give the electromagnets around it something to latch onto, magnetically. They are the reason a stepper can stop and lock at a specific position.



At "1," magnet A is energized. The nearest rotor tooth is attracted to it and the rotor is locked in the position shown as long as the magnet is energized. At "2," magnet B is energized and magnet A is de-energized. The rotor turns clockwise until the nearest tooth is aligned with magnet B. At "3," magnet C is energized and magnet B is de-energized. Again, the rotor turns clockwise until the tooth is aligned with magnet C.

At this point, the cycle starts over: magnet A is energized and magnet C is de-energized. However, by now the next tooth is closer to magnet A than the first tooth, so the rotor again turns clockwise.

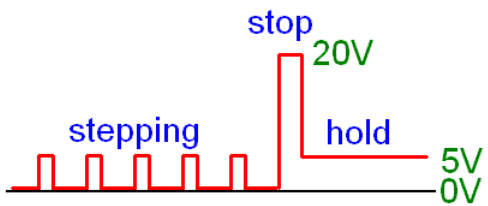


We could feed the electromagnets with regular 3-phase AC, but it's more likely that a stepper motor like this would be fed with 3-phase switched DC, with only one coil energized at a time. If we let the controller keep cycling through the three phases, the stepper will turn like any other 3-phase motor. The difference is, each part of a rotation represents a discrete step. If, at some point, we freeze the voltage waveforms, the rotor will stop with one of the teeth pointing at one of the magnets.

An AC or DC brake stops wherever it stops. A stepper stops in a specific, predictable position and stays there as long as the magnet is energized. That means a controller such as a computer can tell the motor to start from exactly *this* position and move to exactly *that* position by outputting the right number of rectangular-wave pulses. And notice, the controller doesn't need a feedback loop to tell it where the motor is. All it has to do is count, and the motor will wind up in the right place.

Once the motor has stopped in a certain position, continuing current through the magnet will keep the motor in the same position, even if whatever it's connected to is trying to turn it – unlike an AC or DC magnetic brake which will turn slowly in response to an external force. A stepper's usefulness comes from the fact that, while any motor can be told to *run*, only a stepper can be told to *stop*.

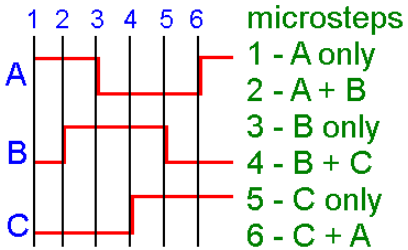
Of course, magnets aren't infinitely strong, so a strong enough twist on the shaft can overcome the magnetic force. The motor can slip a notch, especially if it's started or stopped too quickly. One way to prevent that is to briefly hit the motor with a higher voltage than it could handle on a continuing basis, to create a large momentary starting or braking force.



Steppers come in a great variety of types. In many cases, the rotor is permanently magnetized, so the magnets don't have to be driven all the time – when they are all turned off, the rotor locks in whatever position it's in. Most people own at least one battery-operated clock or watch where the second hand jerks ahead, one step each second. That's a permanent-magnet stepper.

Microstepping

A typical stepper motor has 3-degree steps. Sometimes that's not fine enough. Smaller steps can be obtained by gearing down; e.g. a 10:1 reducing gearbox will provide steps of 0.3 degrees. But smaller steps can also be obtained by **microstepping**. Let's say we overlap the three drive signals, so two adjacent magnets are energized part of the time. In those times, the rotor tooth will stop halfway between the two magnets. We've just turned a 3-degree stepper into a 1.5 degree stepper.

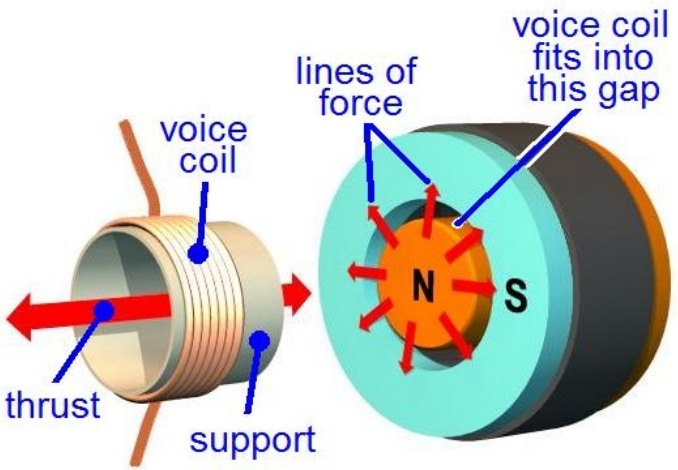


If we want to go farther, we can adjust the voltages to get any position between the two magnets we may want. We can even eliminate the steps, creating smooth analog motion, but with fairly precise position control at each moment and the ability to stop at a precise point. For example, when steppers are used in printers, microstepping allows precise print head positioning.

LINEAR MOTORS

If we think only in terms of motors that spin, we'll miss part of the show. The same principles can be used to create motion in a straight line. Some linear motors are simply regular motors that use a screw mechanism to convert rotary motion to linear motion. But in others, the field or armature actually moves in a straight line.

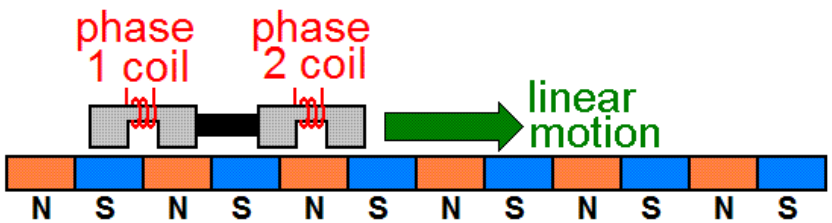
There are probably more linear motors than rotary motors. If that seems like a crazy statement, think of loudspeakers.



In a speaker, a coil of wire called a **voice coil** sits in a narrow gap between two magnetized **pole pieces**; one pole is a cylinder in the center and the other is a donut around it. In the illustration, I have pulled the voice coil out so you can see the parts. Note that the lines of force go in a circle, outward from the North pole to the South pole, across the gap. When an alternating current is sent through the coil, it pushes itself deeper into the gap and out of it, through standard Fleming-rule perpendicular action.

The coil is mounted on a tube-shaped support, and a paper cone is attached to the tube. When the coil moves, the speaker makes sound. This driving mechanism is a real motor, and that's what speaker designers call it. Voice coils are used to focus camera lenses and focus the light beam in a CD or DVD player, and used to move read / write heads across the discs in a hard drive.

These motors have a very limited range of motion. On the other hand, there are trains that use linear motors for propulsion. These are essentially linear stepper motors.

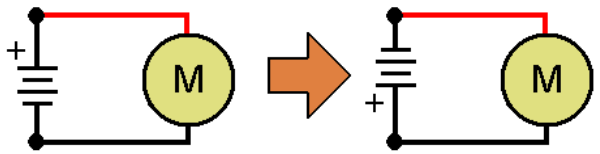


Imagine that – a motor that's 200 miles long!

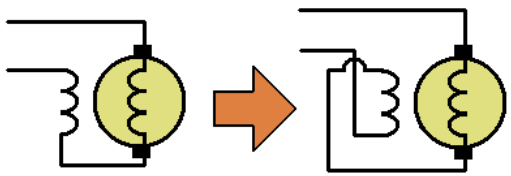
REVERSING MOTOR ROTATION

In theory, the rotation direction of most motors can be reversed. How it is done depends on the type of motor.

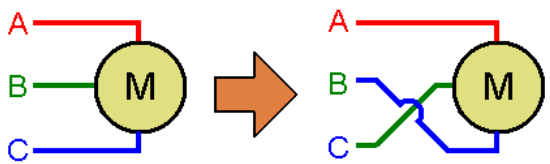
Permanent magnet DC: Since the field is always the same, rotation is reversed by swapping the wires to the rotor or reversing the DC polarity.



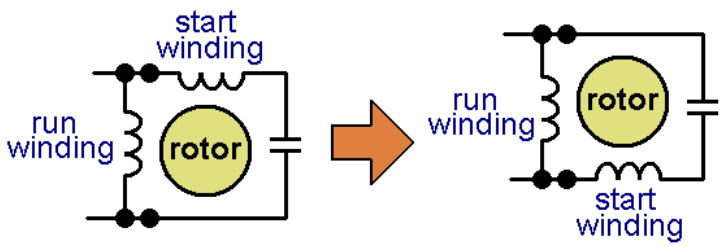
Shunt, series or compound DC, AC or universal brush & commutator motor: reverse the leads to the field or the rotor, not both.



3-phase AC: swap any two of the three wires.



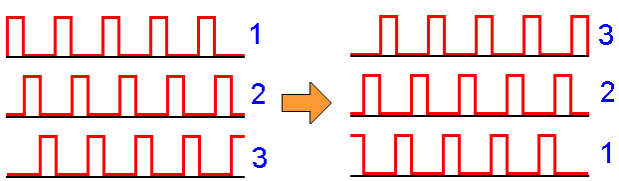
Capacitor-run: if the split phase coil is brought out to separate terminals, rotation can be reversed by swapping the series coil-capacitor string.



Capacitor-start: since the rotating field does not exist when the motor is up to speed, the direction can only be reversed by allowing the motor to stop. Swap the leads of the coil-capacitor string.

Split phase and shaded pole: normally cannot be reversed, because the direction is a physical property built into the motor. Special reversing motors are available but rare.

Linear and stepper: reverse the relative timing of the rectangular drive pulses.



Voice coil: reverse the wires or electrical polarity.

Not all motors are intended for dual-direction operation. It can usually be assumed that a 3-phase motor can spin either way, but that's not necessarily true of the machine it's connected to. In other cases, consult the manufacturer. It is not good practice to reverse a motor immediately while it's turning. Better to let it stop, then reverse it. This caution does not apply to motors designed for quick reversal, including linear and stepper motors.

End of chapter 4

EM5 Chapter 5
THE POWER GRID

Objectives of this chapter:

- *explain why our power system converted from DC to AC*
- *list the components of the AC generation and distribution system and give typical voltages*
- *explain "grid"*
- *describe 3-phase power, delta and wye connections*
- *define "phase error" and "voltage imbalance"; discuss their causes and the problems that result*
- *discuss "single phasing" and why it burns out motors*
- *explain how the same three wires can provide 480V and 277V*
- *describe the 120V / 240V residential wiring system*
- *discuss "smart grid"*
- *discuss "base load," "peak load" and "spinning reserve"*
- *discuss peak shaving and valley filling*
- *define "power factor"*
- *explain how a poor power factor may be improved*
- *discuss the potential and problems of renewable energy*
- *define and discuss "microgeneration"*

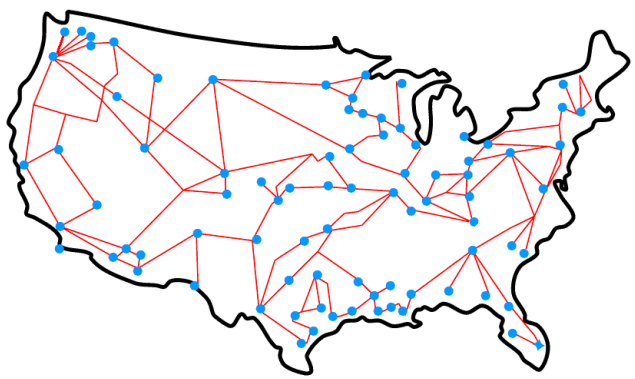
Like motors and generators, our power generation and distribution system was built before there was any such thing as electronics. Like motors and generators, electronics have now become part of the power system to the point where every electronic tech should understand at least the basics of power generation and distribution.

In addition, there are environmental and political forces that are bound to affect technicians, even those who never climb a tower to string cables. The electrical power industry is under pressure from all sides – increasing fuel costs, increasing construction costs, increasingly tight environmental constraints, and citizens who demand increasing amounts of power but want it to happen without building any more power plants or transmission lines. Our existing power system is reaching its limits, and will not be able to handle the expected rise in traditional electric loads . Add new uses such as the the coming conversion from gasoline vehicles to electric vehicles, which is more than probable, and it is obvious that we have no choice but to massively upgrade the system in coming years.

But we can put off the investment for a while, and reduce its cost when it does come, by learning to use our existing power system more efficiently. The buzzword for that is **smart grid**, an electric grid that uses electronic monitoring and control, right down to remote control of individual appliances.

In coming years, equipment from computers to washing machines will “talk” to the power lines they're plugged into, so this isn't just something only power company techs need to know about any more. The purpose of this chapter is to give the technician trainee a broad overview of the power generation and distribution system. We won't be going into great detail and there will be very little math.

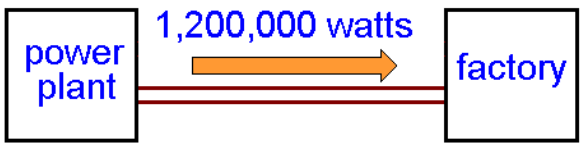
THE HIGH VOLTAGE GRID



We refer to our AC power distribution system as a **grid** because it's all interconnected. Generally, a power plant is built to serve a specific area. However, everybody's local system is connected to everybody else's, and power companies buy and sell power all the time, depending on who has extra power to sell and who needs more power than they can generate. This also increases reliability. If the link between a power plant and a town goes down, we can switch the town over to a different power plant.

The most striking thing about the main cross-country power lines is just how high the voltages are – 300kV minimum, and in some cases more than a million volts, higher voltages than a tech will deal with almost anywhere else.

The voltages are that high because they have to be. Suppose we have a power plant in East Somewhere, and a factory in West Somewhere, 10 miles away. Suppose we want the power plant to supply the factory with 1.2 megawatts of power at the same 120V we get from our power outlets and light sockets. Watt's Law tells us that current will be $1.2 \times 10^6 / 1.2 \times 10^2 = 10^4$ Amps. That's 10,000 Amps.



We know that at normal temperatures, all conductors have resistance, and that means we're going to lose some power between the power plant and the factory. Suppose we've decided the maximum allowable power loss is 10%. Suppose we're also using DC, so we don't have to worry about skin effect.

I'm not going to show the math here, though it would be just a dandy idea for you to work through it yourself – but the bottom line is, if the power were sent from power plant to factory at 120 volts, each wire would have to be more than 4 *feet* in diameter; 5 feet if we use aluminum wire. Anything smaller, and we will lose too much power between the power plant and the factory. And even a 10% loss means 120,000 watts of wasted power.

Obviously, a 120V power grid isn't workable. So what do we do? We raise the voltage. That gives us not just one benefit, but a choice of benefits.

- We can reduce the size of the wire.
- We can reduce the power loss.
- We can send electricity over a greater distance.
- Or we can mix our benefits: we can have a somewhat smaller wire with somewhat less power loss over a somewhat greater distance.

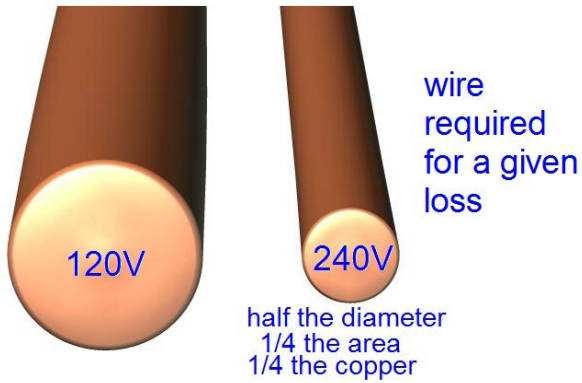
You know from EM1 that power is voltage times current. At a power level of 1.2MW, if we double the voltage to 240 volts, the current is cut in half, to 5,000A. That in turn cuts the voltage drop in half, and the power loss by 75% to 30,000W, which is only ¼ of the 120,000W power loss we started with.

Rule: **For a given conductor size, power loss is inversely proportional to the square of voltage**. Double the voltage, get ¼ as much power loss. Triple the voltage, get $^1/_9$ the power loss.

Or, if we like, we can take our payoff a different way: we can keep the same power loss and reduce wire size instead. Rule: **For a given amount of loss, cross-sectional area of the wire is inversely proportional to the square of voltage**. Double the voltage, we need only ¼ the cross sectional area. Triple the voltage, we need only $^1/_9$ the area. That means we need only ¼ or $^1/_9$ as much copper or aluminum.

Let's see how that relates to wire diameter. Round wire has a circular cross section. The area of a circle = 2π times the radius squared. Turning that around, that means radius is proportional to the square root of the area. Diameter is just 2x the radius.

So, wire diameter is proportional to the square root of area, which is inversely proportional to the square of voltage. The square and square root cancel out, and we're left with the rule: **For a given amount of loss, required wire diameter is inversely proportional to voltage**. This means if we double the voltage to 240V, we cut the wire diameter by half. In the 1.2MW example above, that means we go from a 4-foot diameter wire to 2 feet.



Well, whoopee all Tuesday, we just saved 75% of our copper, but 2 feet is still way too big. Let's see what happens if we boost the voltage a whole lot, say to 120,000V (120kV). That's a 1,000 : 1 boost, so our wire diameter will shrink from 4 feet to about $^{1}/_{20}$ inch, that is, 0.05”, and we will need a millionth as much copper. Imagine – 1.2 Megawatts over a wire the size of a toothpick! Now we're getting somewhere!

What about distance? Well, if doubling the voltage cuts a given wire's power loss to ¼ it's previous value, that means, if we keep the loss and wire diameter the same, it can be four times as long. If we triple the voltage, it can be nine times as long. Rule: **For a given power loss, maximum length is proportional to the square of voltage**.

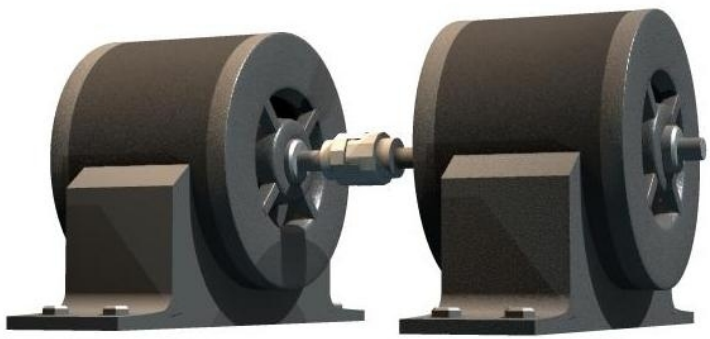
The cool thing about raising the voltage is that voltage vs. loss, voltage vs. copper or aluminum use, and voltage vs. distance are all *square* functions. When we raise the voltage by X, we get X^2 in benefits. Obviously, it's a good idea to push voltages as high as we can.

Nowadays, power plants are in the gigawatt range, a thousand times more power than the example above, so you can see why transmission lines are usually over 300kV. Voltages in that range or higher are called **ultra-high voltages**. There is simply no other way to do the job.

THE SWITCH TO AC

Edison's first, small power grids were DC, but there's a very good reason we switched to AC, over Edison's determined objection. Tesla and his AC motors had a bit to do with that, but the main reason for the switch was more basic. 300kV is a good voltage for long-distance transmission. It's way too high for actual use. Everything in the average home runs on 120V or 240V, and even the monster motors in factories seldom get up to 20,000V. So our 300kV power has to be **stepped down** to a lower voltage at higher current.

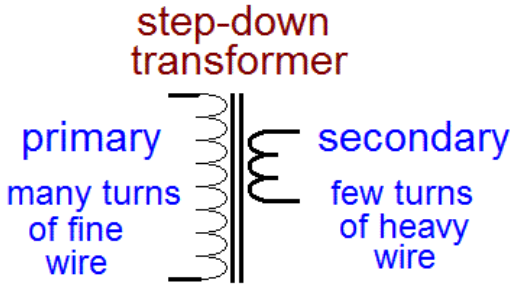
With non-electronic technology, there is only one way to step a DC voltage down, and that is with a **motor-generator** set or **mogen**, which is a motor coupled to a generator. High voltage, comparatively low current power comes into the motor, lower voltage, higher current power comes out of the generator.



Aside from the problems of building a motor to work on 300kV, a mogen has maintenance problems – we're talking about DC, so both motor and generator have brushes – and poor efficiency. And once we've stepped down to 120V, we're not done. Any time we need another voltage change, say for a battery charger, that's another little mogen.

In EM2, you learned about another device that can step voltage down, the **transformer**. A transformer is better than a mogen in every way. It has no moving parts and requires no maintenance, and it's more efficient than a mogen.

But *a transformer only works on AC*. Once people understood that a large-scale power generation and distribution system had to include transformers, they understood AC had to win out. Even Edison's own General Electric Company saw the light and embraced AC. Edison complained. GE's board of directors told him to stuff it.



While we're at it – why did they choose 60Hz? Good question. Transmission losses are higher at 60Hz than they would have been at a lower frequency. Many of the earliest AC plants generated power at 25Hz. Some electric trains in the Eastern USA still run on it. But 25Hz is so low that lights flicker. Arc lights are the worst. Westinghouse found that the frequency had to be raised to 60Hz to eliminate arc light flicker, and since Westinghouse was the 700-lb gorilla of AC in the early days, 60Hz it became and 60Hz it remains to this day, at least in the USA.

As consumers, we're lucky that the frequency is as high as 60Hz. Motors and transformers for 25Hz are a lot bigger, heavier and more expensive than for 60Hz. This advantage is beginning to disappear as switching technology is coming into use, but that's a very recent event and a gazillion traditional motors and transformers are still being made.

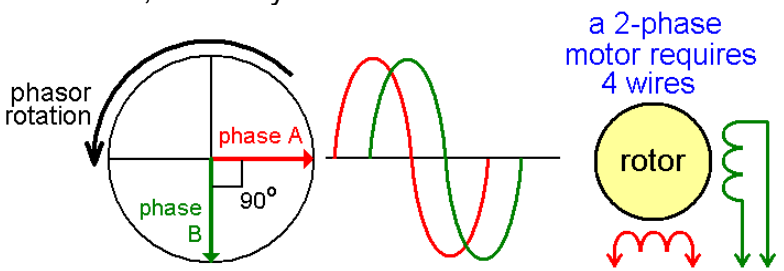
And why did they choose 120V for house wiring? Because GE was already the dominant incandescent lamp maker, and their lamps were made to work on 100V. Edison had goosed his DC generators up to 110V to overcome line loss, and the voltage just kept creeping up over the years as transmission lines got longer. I doubt if the “official” voltage will go higher than 120V, but the “official” tolerance is -5% to +5%, which means the actual voltage may be as low as 114V or as high as 126V.

These small variations are significant because, as Ohm's Law and Watt's Law calculations show, power into a specific load varies with the square of voltage. A 10% change in voltage means a 21% change in power, and that ain't peanuts. So power companies try to keep the voltage as steady as possible.

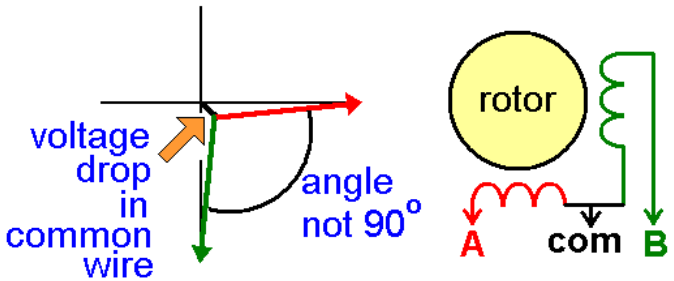
THREE PHASE POWER

For good reasons that are beyond the scope of this study guide, AC power should be as close to a pure sine wave as possible. But our power system is based on not one or two but three sine waves at three phases, 120 degrees apart.

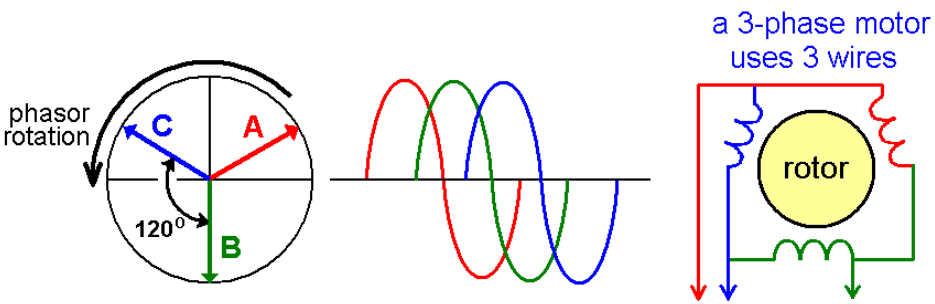
In chapter 4, we studied the rotating-field motors invented by Nikola Tesla, but strictly speaking, Tesla wasn't responsible for 3-phase power. His first polyphase motors and generators used a 2-phase, 90-degree system. The first really big AC plant, at Niagara Falls (generators by Westinghouse, power distribution by GE) was a 2-phase, 245kV, 25Hz system.



The main disadvantage of a 2-phase system is that it requires four wires, two for each phase. You can't use one wire as a neutral common for both, because current flowing in the common will cause a voltage drop, which will change the phase difference away from 90 degrees.

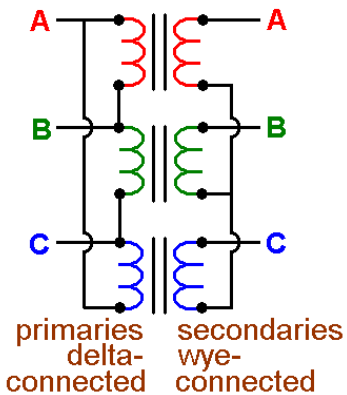


That's a serious problem. When a motor's poles are physically 90 degrees apart, but the electrical phases are, say, 100 degrees apart, the rotor will try to speed up and slow down twice each cycle, and waste a lot of power and create a lot of induction heat in the process. As little as 5° of phase error turns a 1HP motor into a $^{3}/_{4}$HP motor, and makes it run up to twice as hot.



With three phases, we don't need a separate hot and neutral wire for each phase. We have just three wires, all of which are hot, but their phases are spaced 120° apart so there are voltages between the wires. This represents a 25% savings in wire costs, which is a lot of money when a city is 600 miles from the generator that powers it. Motors run more smoothly too.

WYE AND DELTA

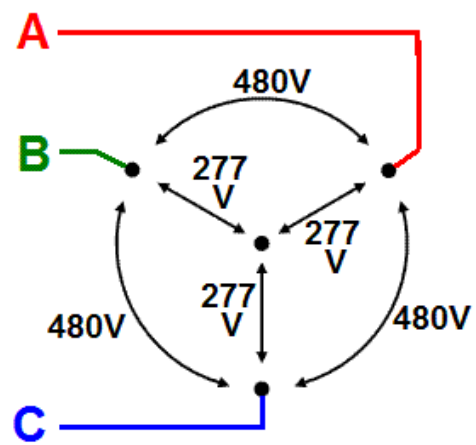


In chapters 3 and 4, we talked about motors and generators being connected in a Delta configuration or a Wye configuration. Transformers can be connected that way too. In the USA, 3-phase power is usually stepped up or down by a trio of single-phase transformers, which may or may not share a single enclosure. Both sides may be connected Delta, both sides may be Wye, or one of each. A line can even have transformers of both types connected.

If you don't see the wye and delta in the illustration above, look again. The wye and delta are not obvious because the transformers are not drawn at 120° angles. But if you trace the circuits, you'll see that on the primary side, each winding is connected across two phases, and on the secondary side, each winding is connected across a phase and common.

DELTA AND WYE VOLTAGES

Using both wye and delta connections, we can get two voltages from the same set of transformers. That's handy because big motors like higher voltages and lighting fixtures like lower voltages. Let's look at a system that provides 480-volt, 3-phase power to a large building. Connecting across two of the phases yields 480V; connecting between any one of the phases and common yields 277V. The three 480V potentials are used to drive 3-phase pumps, air handlers and cooling equipment. The 277V potentials supply fluorescent ceiling lamp fixtures.



You thought lighting was always 120V? Nope. In large commercial buildings with fluorescent lights, it's 277V. In fact, this is so common that a warning is in order: *never* assume the voltage on a light switch in a commercial building is 120V. Many people who aren't aware of this have tapped off the lighting circuit to add an outlet, and ended up blowing up everything that was plugged into it, or they've gone out to Home Depot and bought a light fixture and wired it into an existing circuit, and burned it out.

In wiring specifications, voltage is measured phase-to-phase, so the example above would be called “3-phase 480V.” For any system, Wye voltages are about 58% of Delta voltages.

Since wye voltage is 0.58 x delta voltage, wye current will have to be 1.7 x delta current for the same power level. That leads to some comparative advantages and disadvantages. Where current is very high, a delta design is better because the comparatively higher voltage windings will carry comparatively lower current and require comparatively lighter wire. Where voltage is very high, a wye design is better because comparatively lower voltage transformer windings are easier to build and insulate, and one end of each winding is at or near zero volts, so only one end of the winding needs to be extremely well insulated. It also makes it easier to design fuses, switches and other control components in the system. The Wye configuration is the obvious choice where we need to have a ground reference, a situation we'll look at shortly.

THE GENERATION / DISTRIBUTION SYSTEM

So, let's put the pieces together, starting at the power plant. I'm going to imagine a city called Bigtown, powered by a generating station called Bigplant, 30 miles away from Bigtown's outer-ring suburbs.

The voltages I specify for the Bigplant / Bigtown system are only examples; there is considerable variation among systems. Please note: we're going to be talking about primary and secondary transmission and distribution, and also about transformer primary and secondary windings, which are two completely different things.

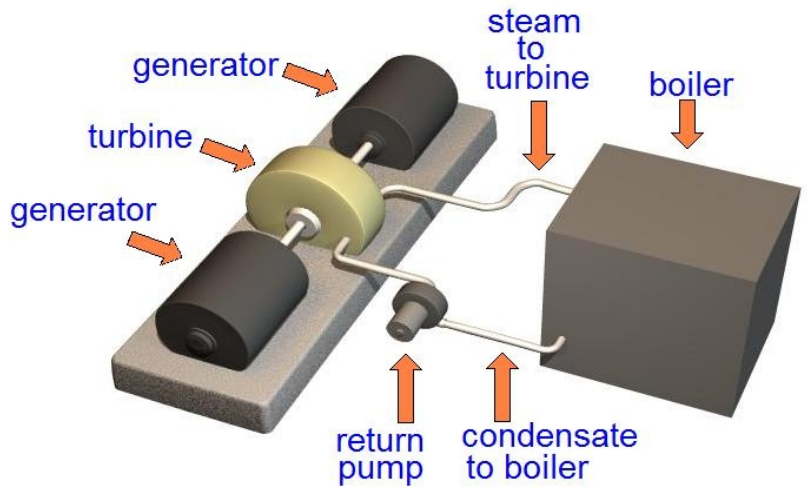
Our generation and transmission system consists of the following:

- Generation at 25kV
- Step-up at the power plant
- Primary transmission at 425kV
- Step down at several transmission stations
- Secondary transmission at 12 to 60kV
- Step down at substations
- Primary distribution at 4 to 13kV
- Step down at the customer's premesis
- Secondary distribution at 120/240/480V

Some systems omit transmission stations and secondary distribution. In these cases, the substations are large enough to take power directly from the UHV wires and step them town to primary distribution voltages.

The Generators

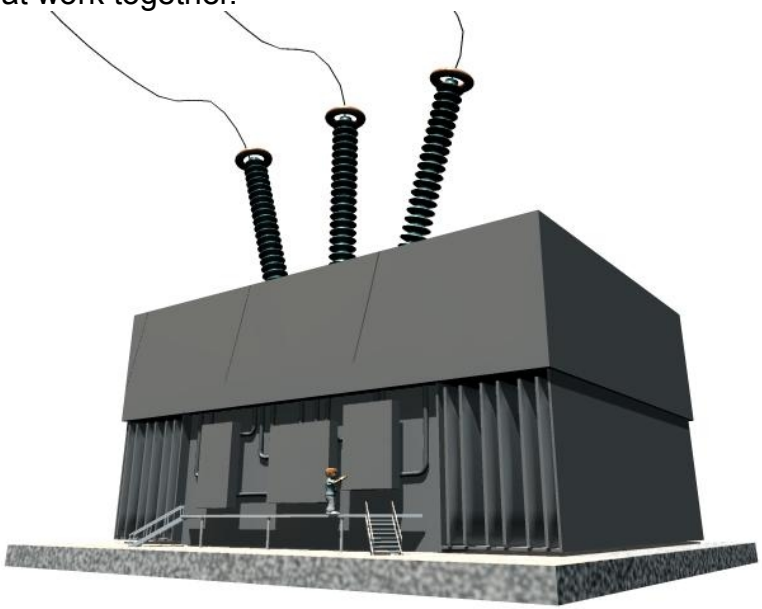
The high-voltage lines between Bigplant and Bigtown are 425kV, but power is not generated at that voltage. Instead, it's generated at 25kV and fed to a step-up transformer. If the total power is 1GW, that works out to about 333MW per phase. 3.33×10^8 watts / 2.5×10^4 volts = about 1.3×10^4 amps, 13,000 amps per phase.



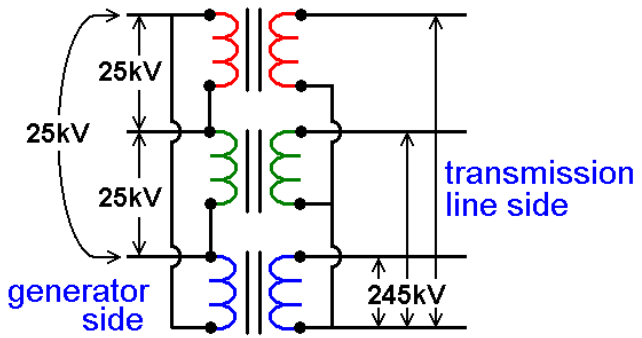
This much power usually cannot be created by one generator. Bigplant has three large boilers making steam, which are fed to multiple turbines driving multiple generators running in lock step. The generators are Delta-connected. To give you an idea how much power we're talking about, a 1GW power plant typically consumes a trainload of coal per day.

The Step-Up Transformer

Power leaves the building at 25,000V, 3 phase, and goes to a **step-up transformer**. The transformer is outdoors because power comes out of it at 425kV, which is hard to handle indoors, and also because it's easier to dissipate heat outdoors. The transformer itself is surrounded by oil for electrical insulation and to carry heat away. When I say "transformer" in the context of a 3-phase system, I'm talking about three transformers, one for each phase, in the same box, that work together.

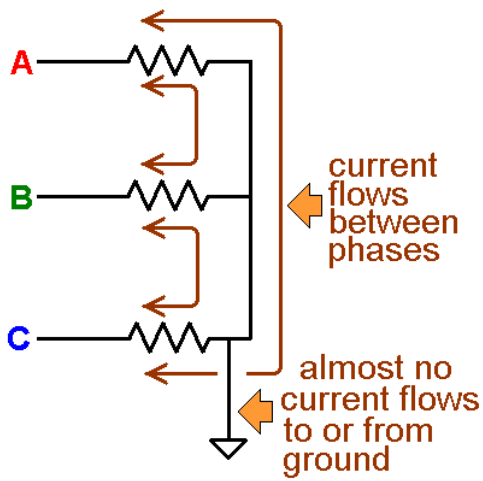


(Note the tiny little person. He's 6 feet tall.)



The primary side of the transformer is delta-connected, with three 25,000V windings. The secondary side is Wye-connected, with three 245kV windings, resulting in 425kV phase-to-phase. 10^9W / 2.45 x 10^5V = about 4,100A, divided among 3 phases, or about 1,360A per phase.

It's important to understand that, though the common center point in a Wye is usually grounded, the main current paths do not pass through the ground. Current flows from each phase through the common point to the other phases.

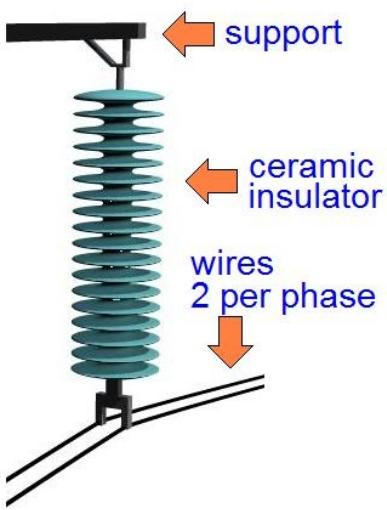


It's not too far wrong to say that Wye and Delta configurations are essentially the same thing because in both cases current flow is from phase to phase. In a wye system, this phase-to-phase current flows through a common point. In a delta system it doesn't.

Now that we've put the power in a high-voltage form, it's ready to be transmitted 30 miles to Bigtown, to where it will be used.

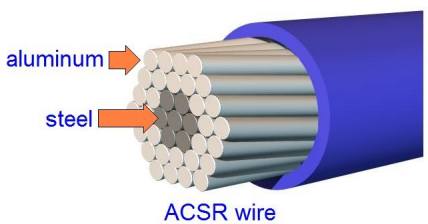
Primary Transmission

A **primary transmission line** is the main 3-phase line (or lines) that carry power from the power plant. They're the wires you see suspended from skyscraper-size steel towers.



Now that we're dealing with such high voltages, we need to space the 3-phase conductors very far apart. Insulating 425kV wires with plastic or rubber would not work; we rely on air and distance for insulation. We also need to attach the wires to supports using long, wavy insulators like the one shown below left. The waviness is to increase the effective distance between the ends of the insulator, discouraging electricity from arcing over.

High voltage transmission wire is usually referred to as **ACSR – aluminum conductor, steel reinforced**. Aluminum is used instead of copper because it's so much lighter, and so much cheaper, that it's better suited to this use even though its higher resistivity means we have to use more of it. The aluminum strands carry most of the current; the steel core provides the strength required to span long distances between towers. Steel isn't a very good conductor, but that doesn't result in large losses because skin effect pushes most of the current outward into the aluminum conductors.



Skin effect is also the reason you often see two wires per phase, as in the illustration to the far left, or even three, spaced a little distance from each other by insulators. A current level of 4,000A suggests that we should be using very large-diameter wire, but at 60Hz, skin effect starts to become a problem when the wire reaches about $^{2}/_{3}$ inch in diameter. So we have to use several wires for each phase instead.

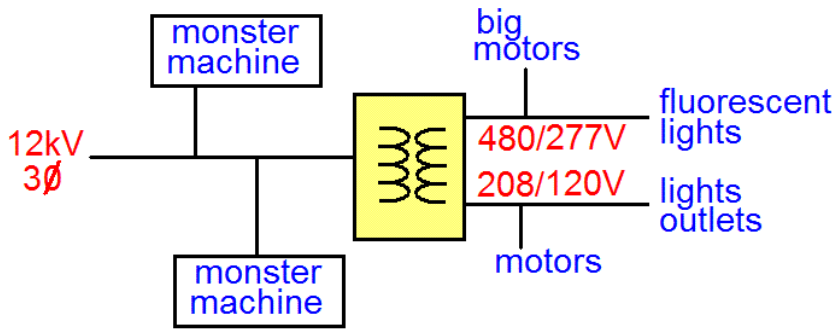
The Bigplant-to-Bigtown line consists of pairs of wires, one pair per phase, suspended from towers by long insulators.

In many cases, a transmission system will have six wires, or groups of wires, instead of three. This provides two 3-phase paths, so if a problem occurs with one the other can still function. It also doubles the amount of current that can be handled under normal conditions.

Secondary Transmission

It makes sense to send the gigawatt generated at Bigplant the 30 miles to Bigtown at 425kV. It does not make sense to run 425kV to every neighborhood and step down to 120V from there. Instead, the 425kV line connects to one or more transformer **transmission stations** that step down to 33kV. These stations are located at several points within Bigtown. Their output is fed over **secondary transmission lines** to **substations** located within a few miles of where the power will be used.

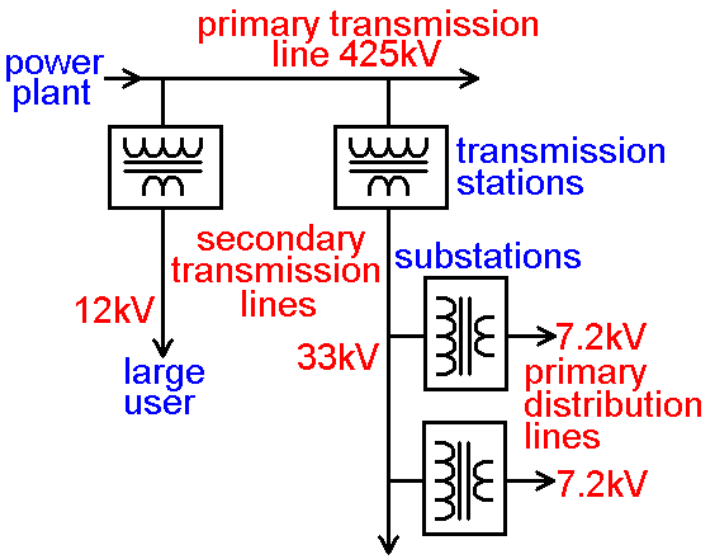
One of the Bigtown substations serves a single customer, a large factory. The substation puts out 12kV. In the factory, there are huge motors that run on that voltage. There are also transformers in the factory to step the 12kV down for other uses.



Primary Distribution

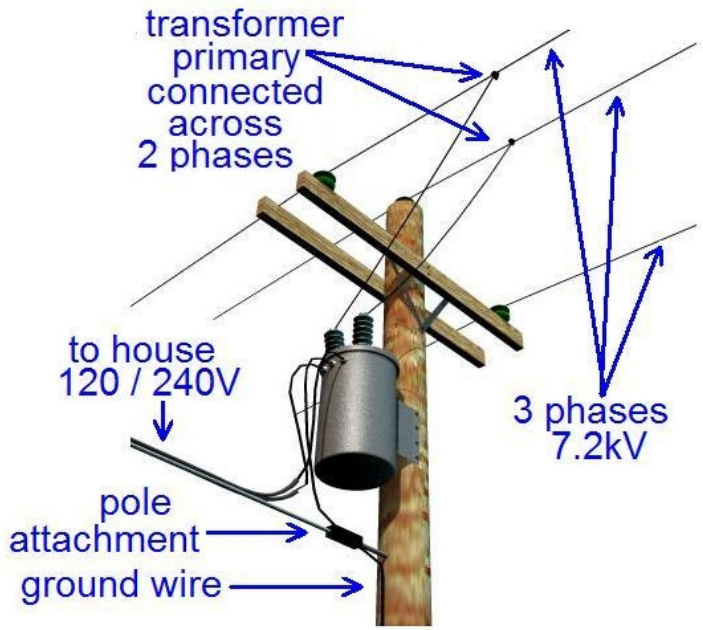
The output of a substation is what is finally distributed to every neighborhood, every block, every strip mall. This is called **primary distribution**. But we still don't want it to be stepped all the way down to 120V. Edison discovered that, at 100-120V, a wire even a few blocks long would show serious voltage drop, and that was back when people were using a tiny fraction of the power we use today.

So, a substation steps the secondary transmission voltage down to a voltage that is still fairly high. The power company in Bigtown has standardized on 7.2kV wye (about 12kV delta), and it's in that form that power gets split up and spread around.

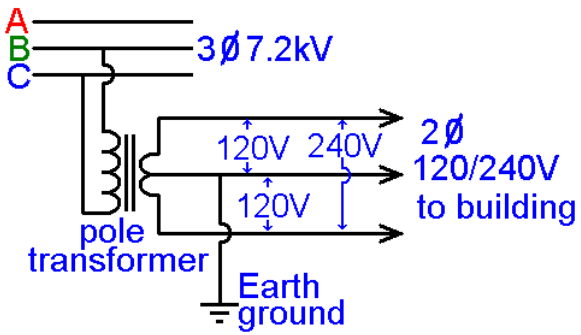


Secondary Distribution

We've gone 30 miles to get to Bigtown, and maybe another 20 miles to get to the other side of it, at 425kV. As those wires cross Bigtown, they feed several transmission stations that drop the voltage to 33kV. The 33kV goes to substations scattered around, which convert to 7.2kV. Now we're in the alley behind your house and it's finally time to convert down to 120V. If you look around you'll see a wooden pole, and near the top of the pole you'll see a big gray cylinder. That's the final step-down transformer in the chain. You will see wires coming out of it to your house, and maybe a couple of other houses. This is called **secondary distribution** and the wires are called **power drops**. Electricians call this transformer a “pole pig.” Electricians are not poets.



There is almost never any need to bring all three phases into a house. The pole transformer is single-phase. Its primary winding is either 7.2kV, designed to be connected between one of the lines and ground, or 12kV, designed to be connected across two of the lines. If you click back a page and look closely, you can see that it's not connected to all three phases.



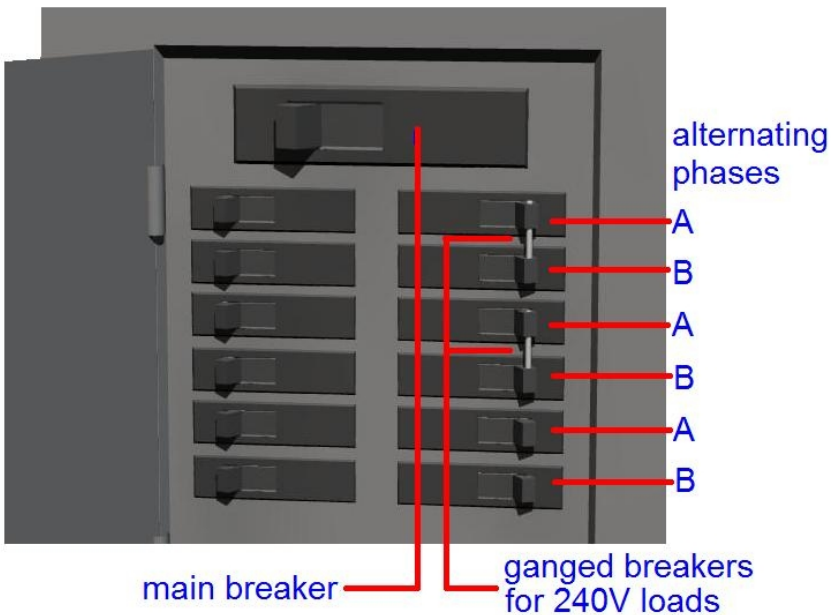
But you will also notice that there are three wires between the transformer and your house. Two are insulated, one (the ground) is bare. We're getting tricky. There are a few things in your house, like the stove, water heater and air conditioner, that draw so much power that a 120V system has trouble supplying it. So, the secondary of the pole transformer is center tapped, and what's fed into your house is actually two 120V wires with opposite polarity. Between either wire and ground, the voltage is 120V. Across the wires, the voltage is 240V. So we have what we need to power both small appliances and large ones.

This is usually called a **2-phase** system, two sine waves 180^{O} apart. I don't like that name, because it can be confused with Tesla's 90^{O} 2-phase system, and because it's sort of incorrect. A better description would be **bipolar AC** or **dual-polarity AC** system. But “2-phase” is so widely used that if you talk about dual polarity or bipolarity, most electricians and many techs will look at you like you had asked them how their Black Plague cultures were coming along.

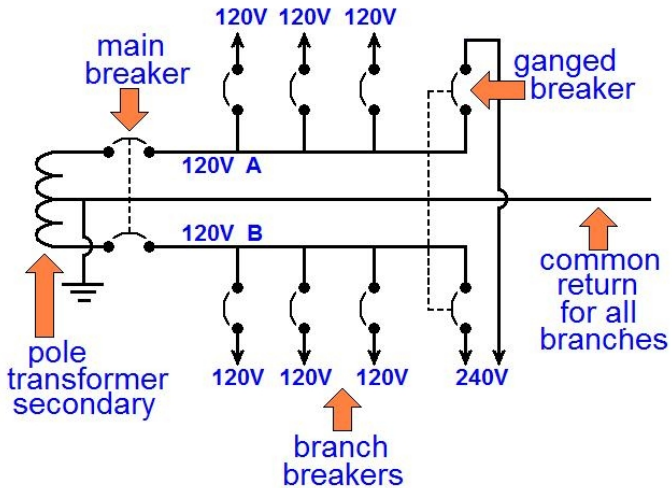
For safety reasons, the transformer secondary's center tap must definitely be grounded. Look at the pole and you'll see a wire going from the transformer to the bottom of the pole. This wire continues underground, wrapped around the pole, to make a good Earth ground connection.

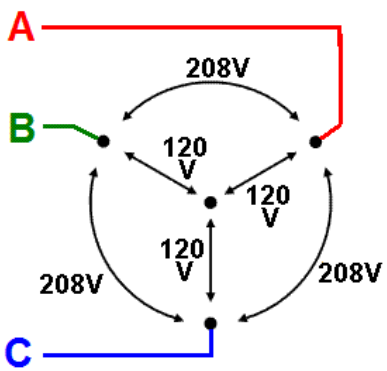
If you live in an area that's been wired or rewired in the last few decades, you probably won't see these wires above ground. **Direct-burial cable** insulation has gotten so good that it's at least as reliable and often less expensive to bury a wire than string it from poles. If you have a pole pig in your back yard, and you don't see wires coming from it, look closely – they follow the pole into the ground. In newer systems, even the primary distribution wires are buried. I live in the country, and it's nice to drive around and not see wires any more. The birds will just have to find someplace else to sit.

120 / 240V comes into the house and into a **breaker panel**. It goes through the main breaker and then through individual breakers that feed **branch circuits**. The feed wires behind the breakers alternate, so as to distribute 120V loads somewhat evenly between the two 120V circuits. If you look at your own breaker panel, you will probably notice that several of the breakers are physically connected together. These are for the 240V loads; if a breaker trips, we want both hot wires to be disconnected.



The schematic to the right is for the breaker panel shown to the left.





120 / 208

Many buildings have motors that require 3-phase power, but they want everything else to run on the usual standard 120V. In these cases, a common option is to use a 3-phase transformer with Wye secondaries, each measuring 120V to ground. The voltage between phases is then 208 volts.

The difference between 220V and 208V is about 6%. Some motors will tolerate that great a voltage range. Other motors have taps in their windings for the two voltages. If necessary, it's possible to get small **autotransformers** that can boost 208V to 220V. Outlets and regular lights are connected in wye between the phases and common.

For a building like a shopping center, the transformer is too big to hang on a pole. Instead, it usually sits on a concrete pad behind the building.

By the way – not that it matters a whole lot – I've been showing the three phases as red, green, blue, but electricians think of them as red, green, yellow. I use blue because yellow doesn't show up well on a video screen.

DC AGAIN

Today, we've got technology Tesla never imagined. We can use solid-state circuitry to turn AC into DC and DC into AC without using mogens. It turns out there's a good reason to do that: at the very highest voltage and power levels, DC is better than AC. Losses are lower with DC, there is no such thing as skin effect, we only need two wires instead of three, and the system is more stable. On the other hand, it's hard to make good, dependable switches for high-voltage DC.

There's no waveform that goes to zero twice each cycle, so it's hard to break the arc when the switch opens. Working with high-voltage DC is not for the faint of heart.

Power still has to be 60Hz sine wave at the end-use point, and the conversion circuitry is huge (the size of a large barn) and expensive. For this reason, DC transmission is mainly used where there is a single start point, a single end point, and a long distance between. One example is the million-volt line from Washington state to Los Angeles, a little more than 1,000 miles long.

DC TO AC CONVERTER, 1971
image Wiki Commons

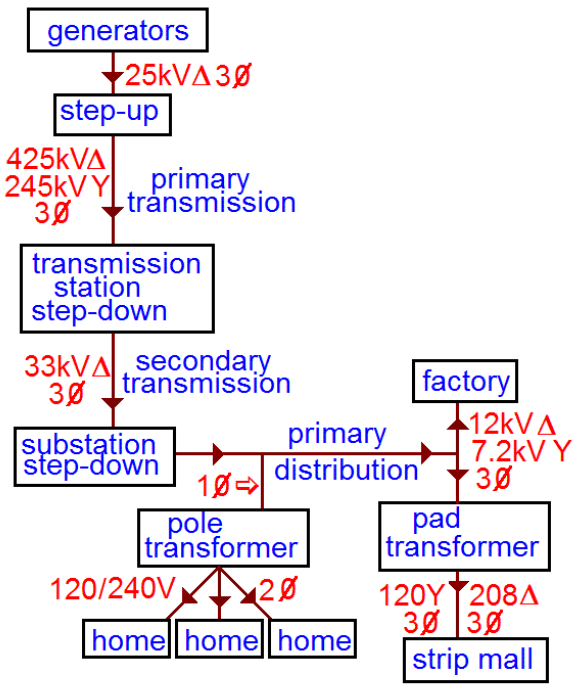
A high voltage DC line is usually a 2-wire system, with one wire positive and the other negative. This reduces the voltage between either line and ground by half. The highest voltage lines I know of are in China, which has vast power needs and vast distances. Those lines are + and – 800kV, 1.6MV total.

THE GRID

Today, we have the infrastructure to interconnect regional power systems so power and generating capacity can be shifted around as needed. That's part of the "smart" in "smart grid," making better use of existing resources. This isn't as simple as it sounds. Our power system grew up gradually, region by region, without a lot of coordination. Building an interconnect grid has meant interfacing systems with different voltages. Sometimes, there's a requirement for a big transformer to change, say, 400kV to 425kV, a difference that is almost meaningless in terms of transmission efficiency but required by circumstances.

Before throwing a switch to join two systems, phase must be carefully monitored. If the phases are not exactly matched when the switch is thrown, the result is something like the explosion of the known universe. Once the two systems are connected, the relative phases still have to be controlled so two power plants don't fight.

Sometimes, an AC → DC → AC conversion facility is built just to allow interconnection of two systems without worrying about phase. The USA really has three grids: eastern and central, western, and Texas. AC → DC → AC conversion stations in Colorado and New Mexico are being proposed so these grids can be linked more easily.



REVIEW

The illustration to the left shows the whole power system, from generator to home.

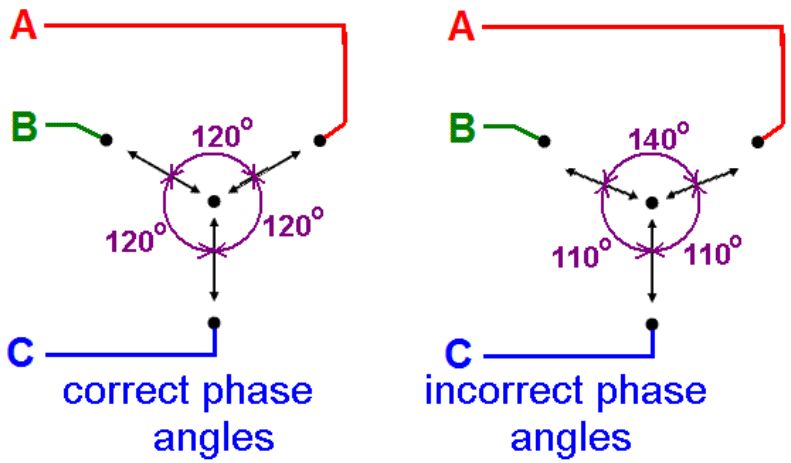
PROBLEMS

I've described our power system in somewhat theoretical terms, operating exactly as it is supposed to. In reality, electricians have to keep constantly adjusting and correcting, just as someone driving a car must constantly make corrections to stay on the road.

In a 3-phase system, the voltages should be precisely equal and the phases should be precisely 120° apart. If they're not, a 3-phase motor will find itself in the middle of three voltage sources telling it to do three different things. If you've been caught in the middle of three people telling you to do three different things, you know how the motor feels.

Phase Error and Motor Problems

The three electrical phases should be spaced 120° apart, as shown in the left-hand illustration above right. This creates a smoothly rotating magnetic field. On the other hand, if the electrical phase angles don't match the physical phase angles as in the right-hand illustration, a motor's field will jerk as it rotates. This causes the magnetic field induced in the rotor to jiggle back and forth once each rotation, cutting across the squirrel-cage conductors and inducing large amounts of wasted current. It also generates a lot of vibration as the rotor tries to speed up and slow down with each revolution.



Voltage Imbalance and Motor Problems

Differing voltages across the phases cause a different kind of problem. Suppose you take a transformer with identical windings and connect it to two different voltages. What do you think will happen? Right, the voltage across each winding will induce an equal voltage in the other, which will fight with the voltage it's connected to. This will give the transformer a hernia.

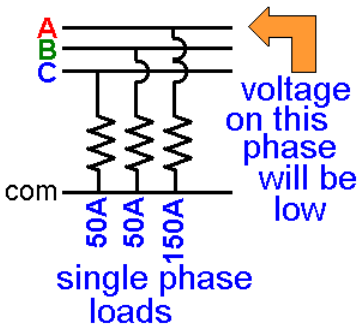
The same thing happens in a motor. A 3-phase motor is a kind of mechanical 3-phase transformer, where current in the three windings create motion and motion generates three equal back voltages in the windings. If the applied voltages are a little unequal, the resulting currents will be greatly unequal. For example, if voltage on one phase is significantly lower than the other two, the motor will act as a generator and backfeed it, trying to shoulder every other load connected to that phase.

All of this is stuff the motor isn't supposed to have to deal with, and it subtracts from what the motor is supposed to be doing, namely cranking the machine it's connected to.

Single Phase Loads

If all loads were 3-phase loads, these problems would not occur. But the vast majority of loads on a 3-phase system are in fact single-phase loads. This includes the “2-phase” 120 / 240V wiring in houses; the two phases are supplied by the center-tapped secondary of a single-phase transformer whose primary is connected single-phase fashion to the grid.

And really, it can't be any other way. How do you make a 3-phase light bulb? How do you convince the manufacturer of a stereo receiver to replace the power transformer (by far the most expensive part) with three transformers? How do you convince every homeowner to rip out all their wiring and start over? For most loads, single phase makes the most sense.



But if there are too many things running on one phase, that voltage will sag below the other two. Also, if you were to draw a phasor diagram and work out the phase angles, you'd see that they were no longer 120 degrees. So what electricians have to do is try to distribute all the single-phase loads among the three power phases so they balance out. That's a moving target as people move in, move out, buy new appliances, build new houses, tear down old ones and so on. Keeps electricians on their toes.

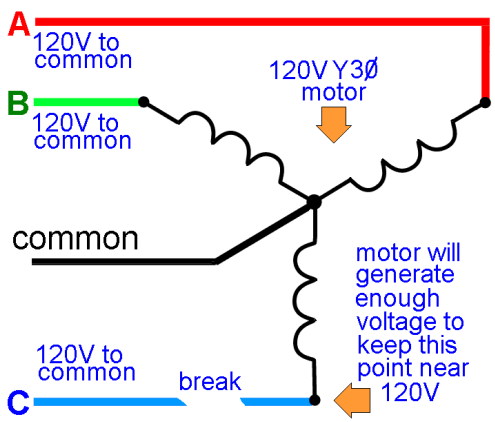
One-Phase Failure

Single-phase wiring also has an advantage. If power fails, it just fails. But in a 3-phase system, one phase can fail when, say, a wire breaks, while the other two phases continue to deliver power. In that event, a 3-phase load becomes a single-phase load, or if it's Wye-connected with a ground, a 2-phase load. To review from chapter 4, this is called **single-phasing**.

With motors, this is worse than if all three phases went dead because the rotating magnetic field disappears but power is still applied. If the motor is already turning, and not heavily loaded, it will keep turning. But a heavily loaded motor will stall, and a stopped motor will not start.

Worse, the breaker may not blow. I talked about that in chapter 4, but now that we understand delta and wye voltages, it's time to take a closer look. Let's say a motor is Wye-connected to a 208V source, with the common winding connection not grounded. 120V will normally appear across each winding. But if one phase goes open, the remaining connected windings will appear in series across 208V, or 104V per winding. A 120V winding with 120V across it will trip the breaker if the motor stalls. A 120V winding with 104V across it may not. So the motor burns up.

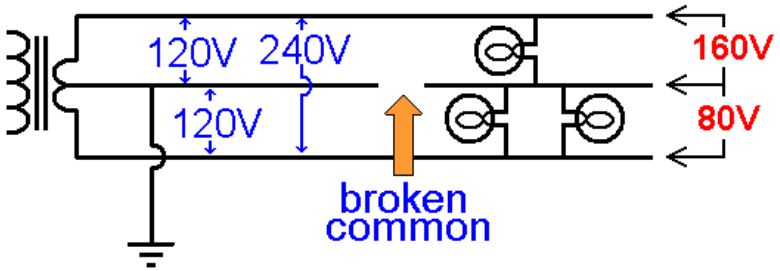
Of course, the danger goes away if we install a power monitor that cuts all three phases if any one goes dead. The problem is determining when one phase has gone dead. Due to the back-EMF, self-generating nature of motors, if there's a motor already running when one phase goes dead, and it's the only load on the line, it will generate a voltage almost equal to the regular applied voltage on that phase. In fact, some people without 3-phase service connect a 3-phase motor to the line and let it run all the time, generating the necessary third phase to run other equipment. (NOT recommended.)



A monitor must measure current in each phase and compare phases. And if there are unequal single-phase loads on the line, that may create unequal currents that cause a false trip. If you're getting the idea that this isn't a slam dunk, you're right.

Floating Common

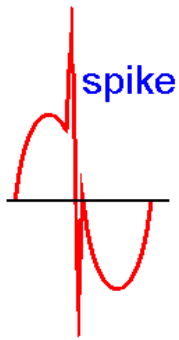
In a 120 / 240V system, strange things happen if the connection between the common wire and the center tap of the pole transformer is broken. Under normal conditions, 120V loads are connected between each of the 120V wires and common. If the common lifts, the result is two 120V loads in series across 240V. Unless they are equal loads, they will divide the 240V unequally. For example, if we have a 100W lamp on one side and two 100W lamps on the other, 160V will appear across the former and 80V will appear across the latter, and the former will burn out.



This is a strictly local problem, and it occurs more often than you'd think. In a building, each branch circuit's hot wire comes from its own breaker in the breaker panel. But commons don't go through breakers. Several commons are routinely connected together by wire nut, and a poorly applied wire nut can come loose and open the circuit. I once lived in a house where we found the commons for five branch circuits twisted together above the kitchen light fixture, and a single #14 wire running from there to the breaker panel. (The white #14 common wire was the return for all five 20-amp branch circuits. Think about that for a moment.)

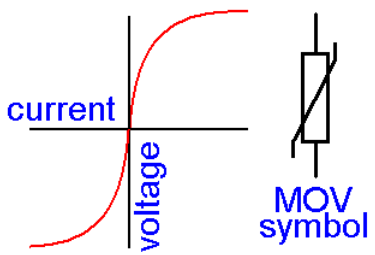
Transients

A transient, often called a **spike**, is a short-duration, high-voltage pulse that appears on top of the regular sine wave. One cause is lightning hitting the power line. I've said that every power system has lightning arresters, but their threshold voltage has to be quite a bit higher than the power line voltage, or they'll start trying to clip off the peaks of the sine waves. Spikes also occur when large a load somewhere on the line is disconnected, especially if it's an inductive load like a motor or transformer.

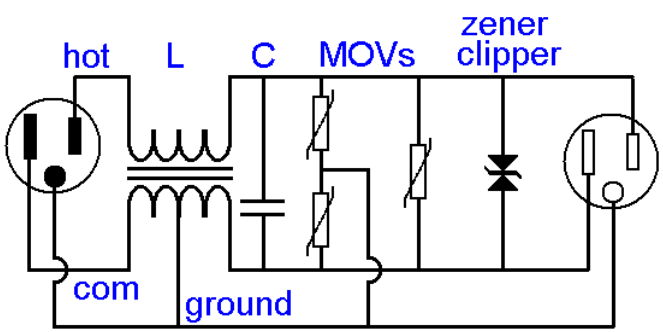


Spikes traditionally haven't been very important, because motors, heaters and incandescent lamps ignore them. They do tend to blow out electronic equipment, and nowadays that means they are a danger to lamps and motors because those things have electronic control now. Power companies cannot completely control spikes, it is up to the user to provide appropriate protection.

The simplest protection is a MOV or metal oxide varistor. At low voltages, a MOV is an open circuit. As the voltage rises to near the MOVs threshold, current starts to flow. If the voltage tries to rise too much farther, the MOV will short out the excess. It's a bit like a dual zener diode, except that the transition between nonconduction and conduction is more gradual.



The small disc MOV in a cheap outlet strip provides some protection, but if it's used in an industrial area where there are lots of transients on the power line, it will soon become ineffective. For sensitive electronic equipment like computers, a more capable (and more expensive) unit that includes inductor-capacitor filtering is recommended.



Load-Generated Interference

Electric and electronic equipment can generate high-frequency energy, and since it's connected to the power line, it can jam that energy right back up the power line, where it's carried to other equipment and radiated into the atmosphere. Anything that switches or commutates can do it, including:

- universal motors
- triac light dimmers
- furnace igniters
- fluorescent lights
- neon signs
- etc.

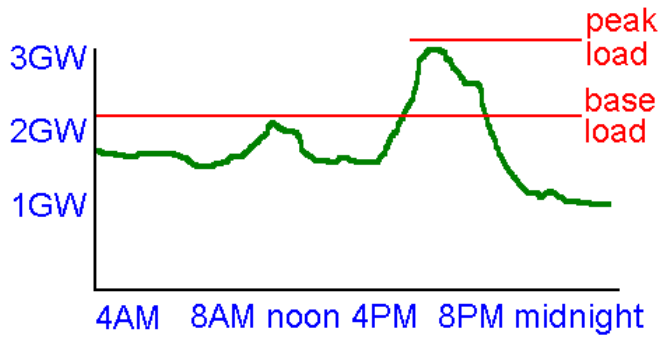
The law sets limits on how much crud a unit can legally produce, but those limits aren't very strict. I have about a dozen switching power supplies, from cellphone chargers to one in my furnace, and they create so much interference I can't listen to an AM or FM station unless it's local.

A tech who learns how to vanquish radio-frequency interference will be able to find a lot of work in the future, because switching power supplies are taking over the world. If a radio-frequency source is interfering with somebody's radio or video reception, the law requires the owner of the offending device to make a good-faith attempt to fix the problem. Personally, I think the FCC should require equipment to be designed so as not to radiate in the first place. It's not that difficult.

Peak Loads

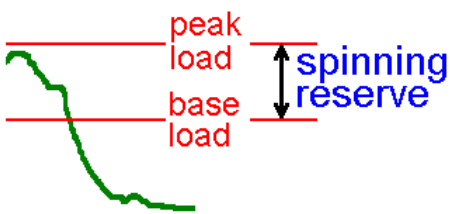
People who design electrical systems make an artificial division at a certain power level. The normal, average total load on a generating plant, plus a little to allow for variations, is called the **base load**. A load in excess of that amount which occurs over, say, two hours is called the **peak load**. Peak loads are the bane of a power company's existence.

With current technology, storing enough electricity to power the grid during peaks is impractical. Batteries just do not store all that much power. Dozens of ideas have been advanced, and none of them are feasible. The reality we have to live with is that power must be generated at the time it is needed.



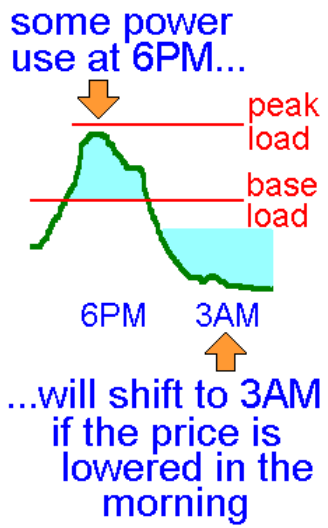
The aggravating thing about peak loads is that they only exist for relatively short periods. That means the power company has to invest in a system that can generate a lot more than the base load – at a cost of billions of dollars – and then, most of the time, let that extra capacity sit idle.

Peaks can be handled four ways. The first way is to just overbuild the power plants and the grid, so the generating capacity to cover the peaks is always there. This is called the **spinning reserve**, and it's expensive and energy-inefficient.



The second is to build the big power plants to handle the base load, and add smaller generators, called **peak shaving** generators, that come online only during peak periods. These may be gas- or diesel-powered, so they can start quickly and come online within a minute. This is another expensive option, as the savings from building a smaller main plant are mostly offset by the cost of having standby generators that are only used maybe 10% of the time. But it is more energy-efficient.

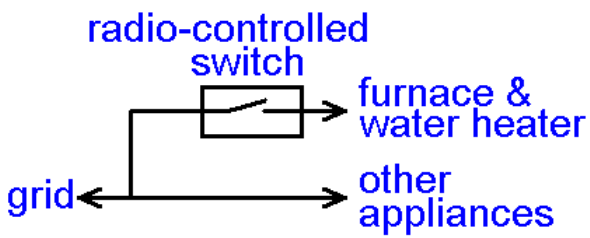
The third is to charge different prices at different times of day, to encourage large users to shift their use to, say, three in the morning. This is called **valley filling**, shifting part of the demand from high-demand to low-demand times.



The fourth way is to simply shut off some customers during peak demand times. This rather strong-armed tactic is used a lot in developing countries.

Power companies have used all these methods since the 1800s. But today, electronic technology is coming to the rescue, providing a way power companies can reduce load swings while hardly inconveniencing users at all. In this scenario, large but non-essential loads shut themselves off during periods of peak demand.

This is part of what people mean by the phrase **smart grid**. The smart grid is in its infancy, but I'm already part of it. I have a radio receiver that the power company uses to remotely shut off my electric water heater and switch my electric furnace over to gas during peak load periods. In return, I get electricity at half price. That may seem like an extreme discount, but peak loads are an extremely expensive problem for power companies, and it's worth their while to do whatever is necessary to shave the peaks.



If everybody's water heaters and furnaces are switched off, that's very effective peak shaving. But because it's done selectively, all their other appliances work. If those people are like me, they won't even know when they're being peak-shaved.

On the other hand, a power company can do remote-control valley filling by turning specific loads on at, say, two in the morning. An obvious example would be the charging circuit for an electric car. If we really do succeed in getting millions of electric cars on the road, there is no way in Helena, Montana that our existing grid will be able to handle them unless the charging is done in the wee hours, when most other loads have been turned off.

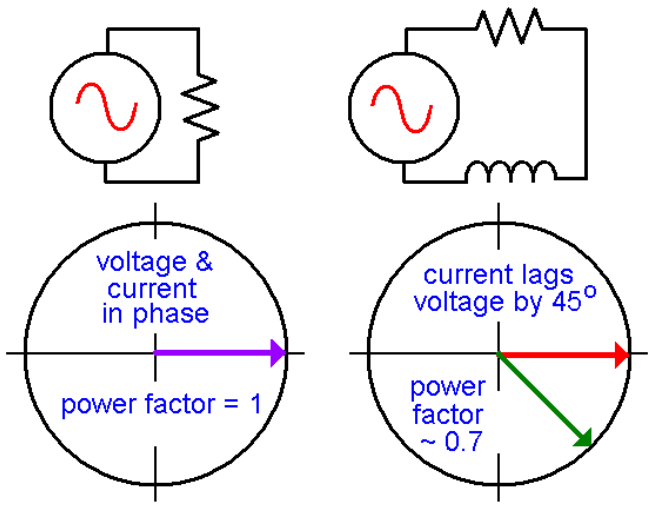
These measures can be made to work now because they are large, permanently connected loads (in the case of electric cars, permanently connected charging stations), remotely controlled by radio. In the future, individual appliances will have this feature built in. A modern, energy-efficient freezer with good insulation, for example, can be turned off four an hour or two at a time without thawing.

POWER FACTOR

The other thing we can do to improve the existing power system's efficiency is to improve the **power factor** of loads connected to it. We're going to look at this in some detail because power factor is becoming a really big deal. If you've gone through the EM2 and EM3 study guides you will understand what follows more deeply, but even if not you should be able to get the basic idea.

If a particular load on a power line is purely resistive, voltage and current will be exactly in step. Power delivered to the load involves simple Ohm's and Watt's Law calculations.

If the load is partly resistive and partly reactive, the situation is not so simple. Resistive and reactive characteristics are usually distributed throughout a load, but we can turn them into lumped quantities for analysis.



Let's say we have a resistance in series with an equal reactance. The two add, but not directly. The resistance is what a mathematician would call a “real” quantity, so to plot it we'd draw a phasor along the X axis. The reactance is an “imaginary” quantity, so we draw a phasor along the Y-axis, creating a 90^{O} angle between the arrows. The resulting load phasor has a phase angle of -45^{O}, and current in the circuit lags voltage by ¼ cycle.

Reactance and resistance both accept power, but only resistance keeps it and uses it. Reactance takes during parts of each cycle and gives back during other parts. Since the actual dissipation of the reactance is zero, you'd think that wouldn't cause problems.

But, even though that power is not used, it has to flow back and forth. That means all the losses in the system apply to it. Worse, since the voltage at the load is divided between the reactance and the resistance, the resistance receives less power than it should. We have to fix that by lowering the load impedance (resistance and reactance both), which increases the load on the power system.

The result is that, the more reactive the load is, the more the power system has to be overbuilt to handle it. If every load had equal resistance and reactance, the whole power system would have to be overbuilt by 40%.

These days, power companies simply cannot do that. No matter where they try to put a new power plant or high voltage line, they are met with opposition from citizens saying, “don't put it here.”

And then there's the economic and environmental cost of burning fuel inefficiently. Thus the emphasis, which will only grow, on improving the power factor of loads.

Power factor is **apparent power**, the power that the generator seems to be making, the voltage across the load times the current flowing through the load, divided by **real power**, the power actually used usefully by the load:

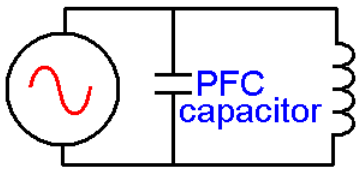
$$\text{power factor} = \frac{\text{apparent power}}{\text{real power}}$$

The power factor of a purely resistive load is 1, which is ideal. The power factor of a completely reactive load would be 0, in which every bit of the power flowing back and forth is wasted, and no useful work is done at all. If we want to minimize the waste caused by a particular load, its power factor should be 0.85 or better.

Power factor is measured in **Volt-Amps**, volts times amps. You're going to say, “okay, that's power,” but it's *not* power, because power is watts used or dissipated, and part of the Volt-Amp measure is not power used.

Power Factor Correction

In most cases, load reactance is inductive. We can cancel this by adding capacitors across the line. This provides **power factor correction** or **PFC**.



There are two primary ways to do this. One is by using actual capacitors. This works for loads up to the size of big machines in a factory. It usually isn't practical on a power-plant scale, both because the capacitor would have to be too big and because power factor can't be corrected at the source, it must be corrected at the load.

The other method is is to use a **rotary condenser**, which is a special kind of motor that sits all by itself and spins all day long. It is designed so that it draws current during the first half of each alternation and supplies current during the last half, which is what an actual capacitor would do.

It's important to note that a PFC unit only improves the power factor from the generator to the PFC unit; if it's installed halfway along the line, the “downstream” half is not corrected. The best place to apply PFC is right at the load, or as part of it.

There is one other way to handle the problem: not create it in the first place. Design every piece of equipment so it has a good power factor to begin with. In much of Europe, it is illegal to sell equipment that doesn't have a good power factor, and the USA is likely to follow suit.

We've covered the major problems; let's move on. Up to this point, we've been dealing with only one method of power generation: use coal, gas or nuclear fuel to create steam; use steam to spin a turbine; use the turbine to turn a generator. Let's look at a few other methods.

RENEWABLE ENERGY

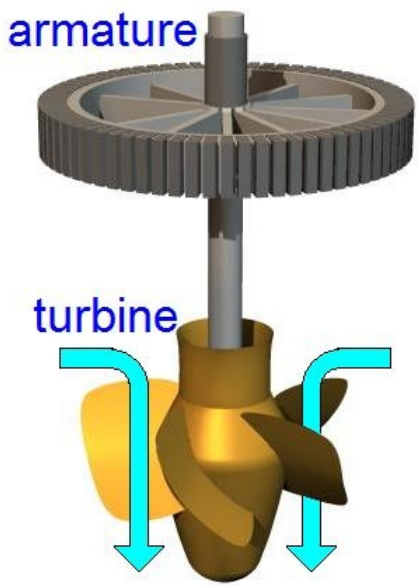
The obvious problem with traditional power generation methods is that fossil fuel gets used up, and at some point we'll run out of it. The other problem is that burning fuel creates waste products. Energy sources which don't involve using up fuel and creating pollution would obviously be better.

But fossil fuels have an obvious advantage too: they are always available, as long as we're willing to dig them out of the ground and as long as we don't run out of them. That's not true of renewable sources. Hydroelectric generators won't run during a drought. Wind generators don't work when the air is calm. Solar collectors don't work at night, or when it's cloudy.

The fundamental problem with unreliable power sources is that, with existing technology, there's no practical way to store large amounts of power. Texas has about 10GW of wind generating capacity. A battery to replace that for the period of one windless day would have to store 240 gigawatt-hours of energy. That's around 300 million car batteries. Not remotely practical. To repeat what I said quite a few pages ago, power must be generated *at the time it's used*. With fossil fuels, this is under our control. With renewables it's not.

HYDROELECTRIC POWER

A hydroelectric generator is almost exactly the same as a coal-fired one, except that water is used to turn the turbine instead of steam, and it turns much slower, which is why the armature has so many poles.



Hydroelectricity is renewable, because rain and melting snow refill the fuel supply. It's clean and does not contribute to global warming. It does have two problems a traditional power plant doesn't have.

First, the water supply is variable. The Hoover dam, which sits across the Colorado River, has had to deal with unusually low water levels in recent years. The other problem is that a coal or nuclear plant can (theoretically) be built anywhere, but a hydro plant must be located where running water is. This often means very long distance transmission lines.

Canada has made great use of hydroelectricity; more of its power comes from water than from all other sources combined. I haven't been able to verify this, but I suspect one of the reasons Canada built a lot of DC transmission lines early in the game was so they could adjust their generators to make best use of varying hydro power without worrying about keeping the output at 60Hz.

WIND GENERATORS

There is no question wind generators can supply useful amounts of power, if we can put up enough of them. The wind generators we already have in Minnesota where I live can, at times, carry the state's entire electrical load.

Since wind isn't reliable, for every kW of wind energy we need another kW of traditional power generating capacity for backup. That means we have to buy our infrastructure twice, which makes the economic value of wind power questionable. However, when we use wind power to reduce fossil fuel consumption of existing power plants, there is no question about economic benefit. With fuel costs rising, power companies are becoming big fans of wind generators. (Which makes them big fans of big fans...oh, never mind.)

As everyone knows, windmills turn at different speeds when the wind varies. For wind power to be useful, the generators must put out exactly 60Hz, exactly in phase with other power sources, so its output can be fed into the grid. This requires conversion circuitry which is no great technical challenge any more, but does require technicians to install and maintain.

SOLAR POWER

Electricity directly from the Sun, via solar or **voltaic** panels, is currently (no, that's not a pun) the only major way of generating power without moving coils and magnets past each other. A solar panel is a large-area semiconductor; existing technology uses silicon.

On a cloudless day at noon, the strength of solar energy is about 1kW per square yard. With existing technology, a good solar panel can convert about 25% of that to electricity. That drops to around 20% by the time the electricity is processed, or 200W per square yard in direct sunlight.

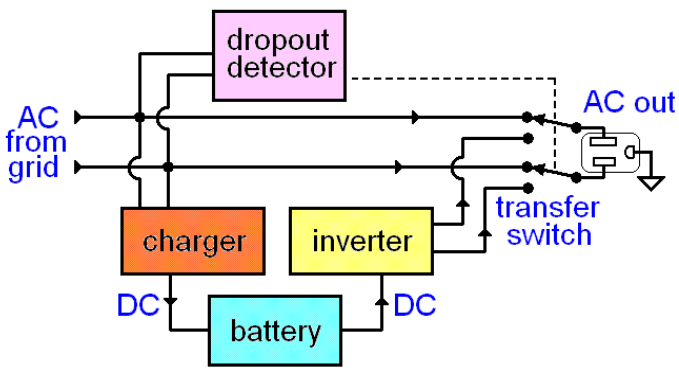
The electricity that comes out of a solar panel must be "processed" because it comes out at a low voltage (a few volts) which varies with the strength of the light hitting the panel. That means it will put out maximum voltage only at noon, and less voltage earlier and later in the day. But most loads require a stable voltage, so an inverter is required to step up and stabilize the voltage. An inverter would be required anyway, if we want an AC output.

STANDBY POWER

For some of us, the 2-ton elephant hiding in the corner, something we're always aware of but seldom mention, is that the grid isn't 100% reliable. I'm finishing up this study guide in February 2014, during one of the coldest winters on record, when temperatures haven't been much above zero for more than a couple of days in a row for months. I'm at the end of a 1,000-foot driveway, which is currently blocked by snowdrifts. I have a little gas heater in one room, just for backup, which can supply me with limited heat for about ten hours. If power goes down longer than that, I'm screwed.

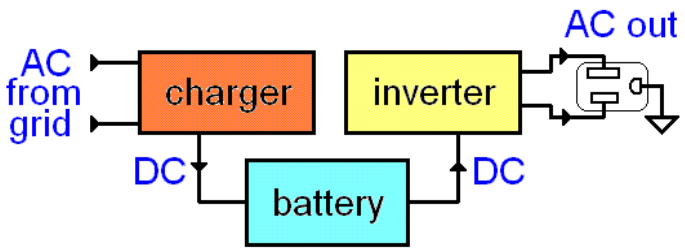
I'm not the only one. Think of hospitals, which have patients hooked up to all sorts of electronic monitoring equipment. We've gotten so good at making electricity serve our needs that we can hardly be without it now. So we've devised various kinds of emergency power supplies, at least for critical equipment.

The most common is the battery-operated **UPS** or **uninterruptible power supply** used to keep a computer from crashing. A UPS consists of a battery, an inverter to change battery voltage to 120VAC for output, a charging circuit to keep the battery charged, a detector to tell the UPS when grid power is down, and an automatic bus transfer switch. This switch is necessary because you can't just connect the UPS output to the dead power line; it would try to backfeed the whole dead part of the grid. At worst, it could electrocute someone working on the line.



A battery-operated UPS can go into operation and replace the grid supply within a single 60Hz cycle. For larger loads, a generator is used in place of a battery. Naturally, there's a longer delay because it takes the generator a while to get up and running.

For loads that cannot tolerate a single cycle of power outage, a battery-operated UPS runs continuously, with grid power converted to DC to keep the battery charged at the same time an inverter is converting battery voltage to AC.



Inefficient? Sure, but sometimes, as with life safety equipment, efficiency isn't our main concern.

MICROGENERATION

The history of electric power generation is one of consolidation: many small plants being replaced by fewer, larger generating plants, located ever farther from large population centers. The economics of coal- and nuclear-powered plants work out best at power levels of half a gigawatt and up.

But in some ways, the trend is reversing. Because we've discovered so much natural gas in recent years, and because it burns so cleanly, there is no reason why small gas-powered generators cannot be located in neighborhoods. This is one possible way to solve the peak-load problem without erecting new high-voltage transmission lines.

To encourage wind and solar power, many jurisdictions have passed laws saying that, if your windmill or solar panels generate more power than you need, you can backfeed the surplus up the power line and the generating company has to buy it. In this case, a simple bus transfer switch is not acceptable. Wind and solar power sources connected to the grid must include circuitry to monitor what's happening on the grid, only backfeed under the right conditions, and not try to connect if the grid is down.

What all this means is that our simple, centralized, top-down power system is going to morph into a complicated, dispersed network requiring lots of highly trained technicians. This will take 30 years – meaning that any tech who trains to work in the energy sector will find good-paying work for a long time.

End of chapter 5

If you're interested in a career in new-energy technology, check out the ETA certifications in solar and wind power and electric vehicles.

EM5 Chapter 6
CIRCUIT CONTROLS AND PROTECTION

Objectives of this chapter:

- describe the difference between snap and non-snap switches; define “hysteresis”
- explain the difference between control and power circuits
- define “pole,” “throw,” SPST, SPDT, DPST, DPDT
- describe screw, solder and push-on termination; give advantages and precautions of each
- describe various switch symbols
- define “relay,” “solenoid,” “contactor”; list various uses
- explain how buzzers and bells operate
- list and explain fuse ratings
- describe thermal and magnetic breakers and show their symbols
- explain the operating principle of a GFI
- explain the operating principle of an arc-detecting breaker
- explain the principle of current-limited circuits

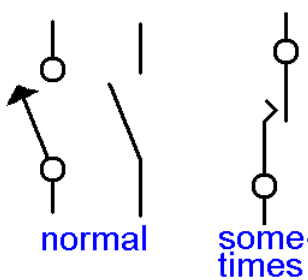
This chapter is a recap and extension of material first presented in the EM1 study guide. Even if you have gone through EM1, that was a while ago, and a refresher is in order. Also, we're going to go into more detail.

SWITCHES

A switch is such a simple thing, you'd think there would be nothing to talk about when it comes to switches. Ya make a circuit, ya break a circuit. But there's lots more to it: types, ratings, reliability concerns etc. Sometimes it doesn't matter what kind you choose, any old one will do. Other times it does matter.

In this chapter, we're going to study:

- mechanically operated switches
- electrically operated switches (relays, solenoids, contactors)
- indicating and alarm devices
- circuit protection devices (fuses, breakers)



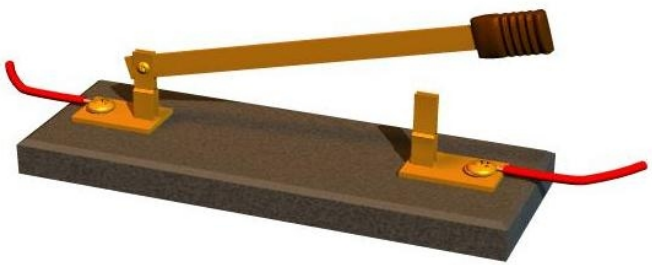
The illustration shows the two schematic symbols normally used for switches. Occasionally, especially when a switch is intended for use in a “dry” circuit (a circuit that carries no significant power, e.g. a video signal), you'll see a switch contact shown with a little hook in it.

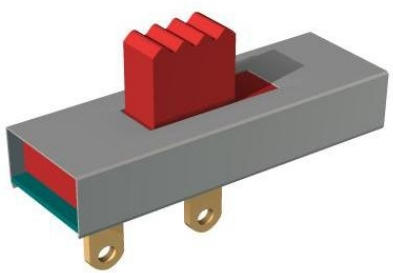
Mechanically-operated switches can be divided into two groups:

- those that snap
- those that don't

Why does it matter? Because if you open a switch slowly when it's carrying high current, you can get an arc across the contacts. Arcing creates extremely high temperatures – they use it for welding – and the switch can be destroyed, along with the stuff around it.

The simplest switches are non-snap switches where contacts slide or are pressed into place. Old horror-movie type switches, known as **knife switches**, are one example.



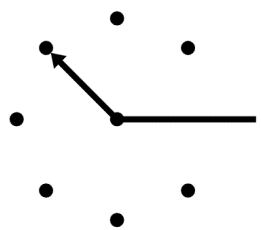


Small **slide switches** are used a lot in electronic equipment. A shorting bar slides into place across contacts to complete a circuit.

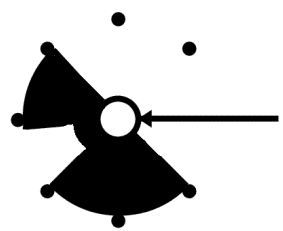
Non-snap switches are simple and comparatively cheap. In a "dry" circuit situation, they work fine.

Rotary switches, and linear switches with many positions, are usually slide switches even when they shouldn't be. The range select switch in a meter is a slide switch made into a circle. The schematic symbol is like a regular switch with more positions, or if it's complicated, the rotary part will be shown as blades.

The blower switch in a car is a slide switch, even though it handles lots of current. In my old Subaru it arced so much it melted. Bad design, but everybody does it.



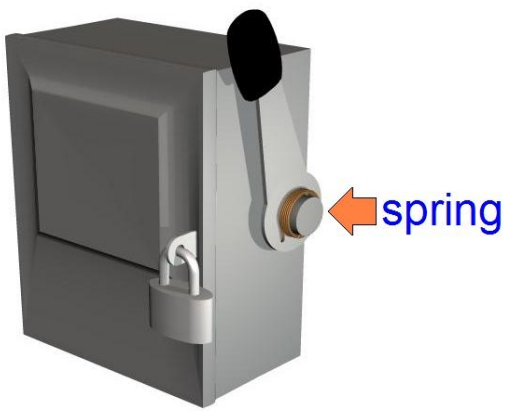
the usual

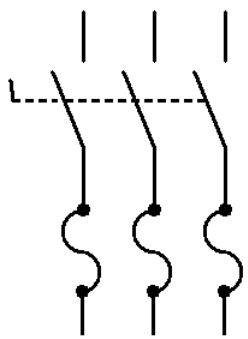


blade representation

Snap switches include a spring mechanism to cause the contacts to always open and close quickly, no matter how slowly you move the lever. This insures that little or no arcing will occur as long as the switch is used within its specified voltage and current limits. You have to push the switch a little past its mid-position for it to turn on, and then push it back a little past its mid position to turn it off. This difference between the “on” and “off” points is called **hysteresis**.

One example is the modern relative of that old knife switch, found in AC power line control boxes The illustration shows a common 3-phase type, with three knife switches and three big fuses. This is often called a **disconnect box**. Typically, all the power in a building runs through it.

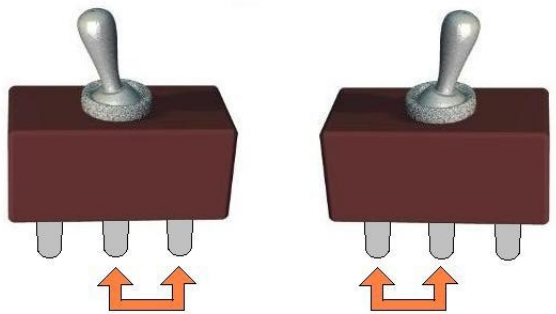




3-phase disconnect with fuses

When several switches are physically connected so they all work at the same time, they are called **ganged** switches. The difference between the disconnect box shown at lower left and the old knife switches is that there's a spring to make sure that when they open, they snap open all the way, all at once. I zoomed up the spring part of the box so you can see what I'm talking about.

A switch that mounts in a hole in a panel, with a lever to operate it, is called a **toggle switch**. Most toggle switches are snap-action, especially if they're meant to handle DC, which is much more arc-prone than AC. The operation of a toggle switch is opposite to what you'd expect; the contacts are closed when the toggle is away from them.



terminals away from the toggle are closed

VOLTAGE AND CURRENT RATINGS

Switch ratings provide a very rough guide to the maximum voltage and current a switch can handle. Exceeding these limits can cause the switch contacts to develop pits, which will ruin them over time. In a machine control application, if the switch ratings are so far exceeded that the contacts weld together, the machine cannot be turned off. Needless to say, this may be a very dangerous situation.

A typical switch might be rated for 10 amps in a 277VAC circuit, 20 amps in a 120VAC circuit, and 1.5 horsepower in a motor circuit at any voltage between 120VAC and 250VAC. If the switch also has DC ratings, the current limits are likely to be lower because of DC's arcing problem.

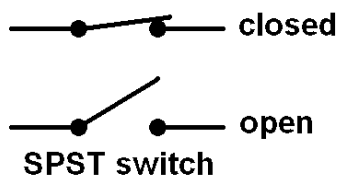
Automotive switches, designed and rated for 12V operation, should not be used in higher-voltage circuits, no matter how pretty they are. Their internal construction may not be able to withstand the higher voltages.

When selecting a switch, pay attention to what it was designed for. Switches are generally divided into **power** switches, which are designed to switch high current, and **control** switches which are meant to be used in low-current circuits and in dry circuits where no significant current is being switched, e.g. a video switcher. Obviously, you can't use a low-current switch in a high-current circuit. Less obviously, it's not good practice to use a high-current switch in a low-current circuit. A high-current switch depends on that current to keep its contacts clean. In a low-current circuit, it may become unreliable.

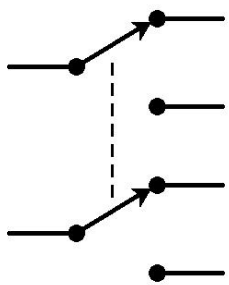
Don't assume that just because a switch is big, it can handle high current. Industrial control switches are made large so you can grab them easily, and so they can withstand a pounding in an industrial environment. But they may not be designed for high current. Read the specs.

POLES AND POSITIONS

The simplest switch has a single circuit and only one position where the contacts are closed. That's called a **single-pole, single-throw** or **SPST** switch. Granted, there are two switch positions, but only one counts because only one position results in a closed circuit.



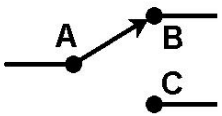
A switch can be made to open and close more than one circuit at a time. One example is that disconnect box with three knife switches ganged together. Each switch circuit is called a **pole**. In the schematic symbol, a broken line indicates that the poles are ganged mechanically,but not connected to each other electrically.



DPDT switch

Finally, a switch with two poles and two closed positions would be a **double-pole, double-throw** or **DPDT** switch. Those four letter names should be memorized, you'll run into them all the time.

Beyond "double," we use numbers. A rotary switch with 6 poles and 8 positions would be a 6P8T switch.

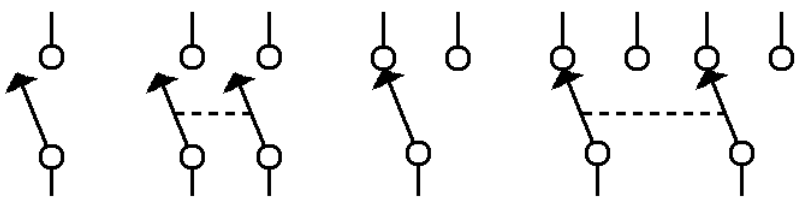


SPDT switch

A switch can also make contact in both positions. An example would be a switch that chooses between two video sources. Each position is called a **throw** – you throw the switch one way, you throw it the other way. I suppose this is a holdover from the days when switches were the size of shoeboxes.

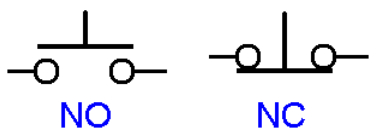
Words are also used to describe positions. A single-throw switch would be described as **ON-OFF**, while a double-throw switch would be **ON-ON**, that is, "on" in both positions. This is handy when you have a 3-position double-throw switch with an "off" position in the middle: an **ON-OFF-ON** switch.

A switch with two poles, but only one closed position, would be a **double-pole, single-throw** or **DPST** switch. A switch with one pole but two closed positions would be a **single-pole, double-throw** or **SPDT** switch.



PUSHBUTTONS

The most common type of pushbutton is the **momentary** type, one that only closes as long as the plunger is held down. This is called a **normally open** or **NO** pushbutton. The opposite type is the **normally closed or NC** pushbutton, where the contacts are normally closed and only open while the plunger is pushed down. A normally closed button is commonly used to break a latched circuit and stop a machine.



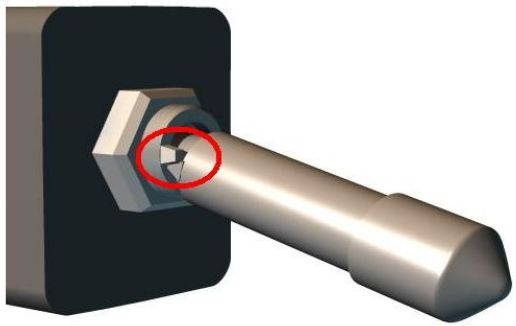
The other type of pushbutton is the **alternating**, on-off type. I've got one right in front of me. Push it once, the computer turns on. Push it again, the computer turns off.

A pushbutton that does not have snap action should never be used to directly switch high current, the potential for arcing is too great. In industrial systems, when you see a monster pushbutton, the reason it's that large is so it will be easy to hit. But, like a monster switch, its contacts may actually be light-duty control contacts.

MOMENTARY SWITCHES

Switches can also be momentary, in which case the word descriptions will use parentheses to indicate momentary positions. For example, a switch that is normally off, and only turns on while you're holding it, would be an **OFF-(ON)** switch. A 3-position switch that closes when pushed to either side, but returns to the center position when you let go, would be an **(ON)-OFF-(ON)** switch. You'd find one controlling an industrial garage door or forklift.

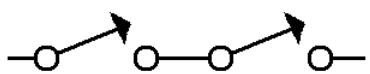
SAFETY AND LOCKOUT



Some switches are made to prevent accidental operation. One type has little ridges that lock the switch in place; you have to pull on the toggle before you can move it. It's pretty hard to imagine a situation where you'd pull on a switch by accident.

Another type of safety switch has a cover over it. You have to lift the cover to get at the switch. Again, hard to imagine doing it accidentally.

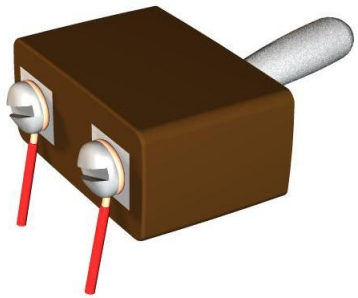
It's also possible to wire two switches in series, so both have to be turned on for the circuit to function. Often, these are key switches, requiring two different keys held by two people. The counting rooms in Las Vegas have two-key access systems of this kind.



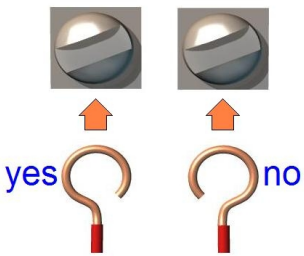
safety / security: both must be closed

CONNECTIONS

The three most common switch connections are screw, solder and push-on.



Screw connections have the advantage that you can connect any kind of wire, as long as it isn't too large. Just put a hook in the end of the wire, put it under the screw, and tighten it.

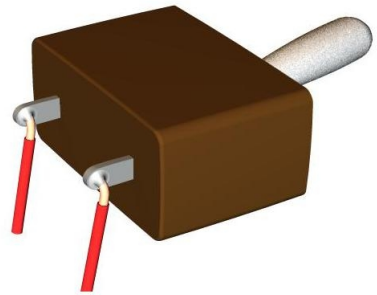


The wire should hook around the screw clockwise, so the screw pulls it in as it tightens rather than pushing it out.

Screw connections work best with solid wire. The main problem with stranded wire is keeping the wire from squishing out from under the screw. *Do not* tin the ends of stranded wire with solder to keep this from happening. Solder is soft. Under the pressure of the screw head, the solder will yield over time, and the connection will loosen.

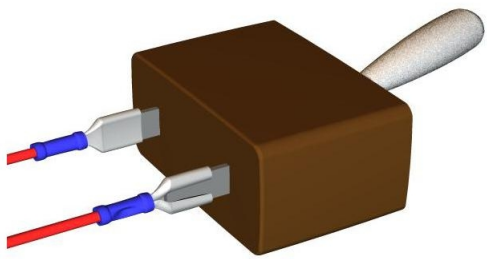
Solder connections, if done right, are extremely reliable. The problem is, soldering is often not done right.

The wire and the contact must both be clean and shiny, and the tech must be skilled at soldering. Otherwise, the joint itself may crumble or solder may come loose from the wire or contact. This is known as a **cold solder joint**.



When soldering on the jobsite, there's a danger you'll set something on fire. A soldering iron is hundreds of degrees hotter than the flash point of paper or cloth. This is a good place to use a soldering gun if you can. Within a few seconds after you release a soldering gun's trigger, it is no longer hot enough to start a fire.

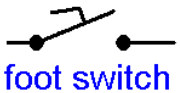
Push-on termination is fast and reliable, as long as you crimp the clip onto the wire properly. I've seen a lot of improper crimping, to the point where the wire just falls out of the clip – even in high-voltage situations where this is really dangerous. We'll be talking about crimping in a later chapter, and you can find crimping tutorials on the Internet. It's a good skill to have.



SPECIAL SWITCH SYMBOLS

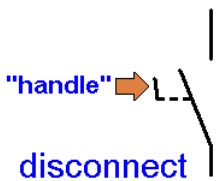
There are dozens of symbols to indicate special functions. Some of these symbols are used by only one manufacturer, but others are universal.

Limit switch – a switch on a machine, often with a roller, that makes or breaks when part of the machine reaches a certain point. The triangular part is meant to suggest a ramp.



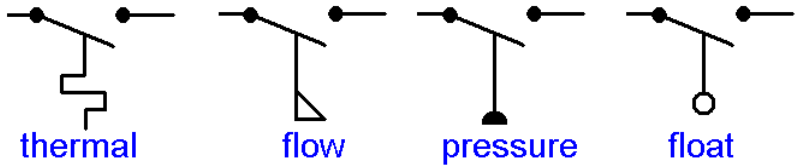
Foot switch – indicated by a bent line.

Disconnect – a switch with a dotted line with an angle in it, meant to suggest a lever or handle.



A number of symbols describe automatic switches typically used to limit machine functions:

Temperature limit (thermal) switch – indicated by a wiggly line suggesting a heating element.
Flow switch – a switch with a vane.
Pressure switch – a switch with a half sphere.
Float switch – a switch with a circle representing a hollow float device

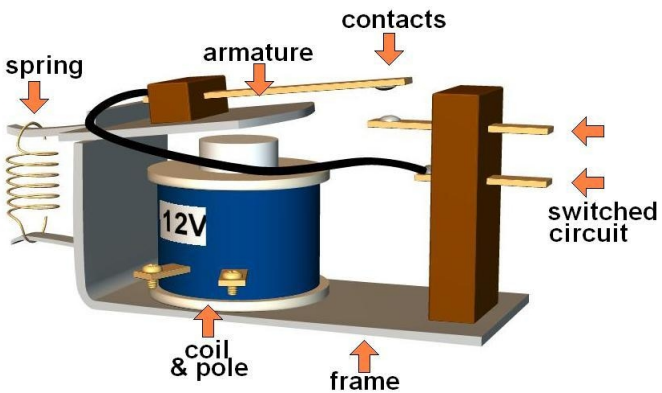


A switch's operation can be checked in a circuit, with power applied, using a voltmeter. When the switch is "on," almost no AC or DC voltage should appear across the switch. After all, an ideal switch is a short circuit. When the switch is open, whatever AC or DC is present in the circuit should appear across the switch terminals.

RELAYS

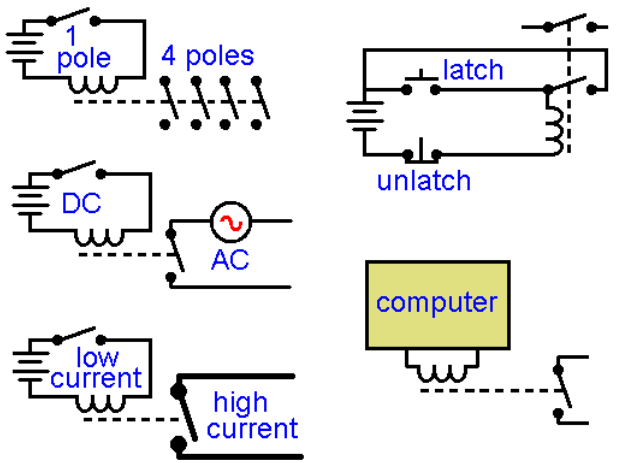
A relay is an electrical switch, operated electrically. Back in the telegraph days, a relay was sometimes called a "repeater," which is a good description. You close a pair of switch contacts, which energizes the relay, which closes a pair of switch contacts.

A relay consists of an electromagnet wound around a ferromagnetic core called a **pole piece**. When it's energized, it pulls a moving **armature** toward it. Contacts attached to the armature close or open. There can be any number of contacts, in any combination of normally open, normally closed or double-throw. The traditional symbols shown on the preceding page use a dotted line to indicate that the coil's magnetism moves the contacts.



A relay is typically used when you want to:

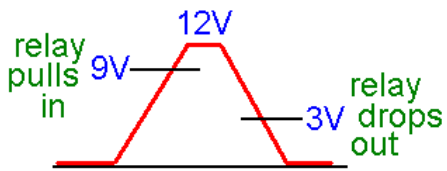
- use one closure to control several closures
- use one type of electricity to switch another type
- use a small current to control a large current
- use a momentary closure to latch or unlatch a closure
- use a computer or other electronic control device to operate a machine



Relay contacts are like any other contacts; they have maximum voltage, current, and often horsepower ratings, and AC ratings are different from DC ratings. Like switches, there are power and control types.

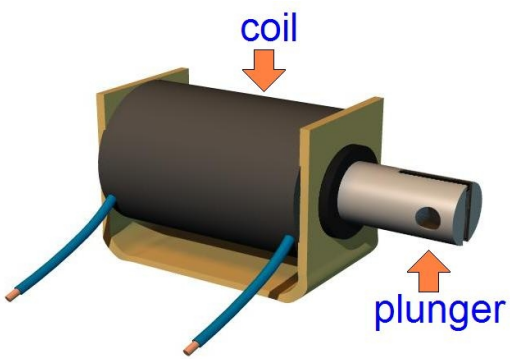
Relays almost always have snap action. You remember from EM1 that the pull exerted by a magnet (the pole piece) on a lump of ferromagnetic material (the armature) gets stronger as the two get closer to each other; the function is the inverse of the square of the distance. That means, the closer the armature, the stronger the pull, which brings the armature even closer. In practice this means that once the armature begins to move, it will move until it's against the pole piece. With a relay there's almost no such thing as “half on” or “half off,” which is a nice bonus.

This also means that the **pull-in voltage** which causes the contacts to “make” is different from the **dropout voltage** which allows them to “break.” A 12VDC relay will typically pull in at about 9V, but once it's pulled in, will not drop out until the voltage falls to about 3V. Yep, our old friend hysteresis.

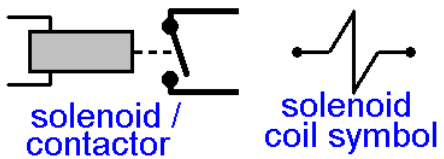


SOLENOIDS AND CONTACTORS

A solenoid is like an electromagnet except that, instead of pulling an armature toward a pole piece, the coil surrounds the armature and pulls it inside. A solenoid is used where the armature must move a longer distance, or be pulled harder, than would be practical with a relay. In a solenoid, the armature is often called the **plunger**.



In line-voltage AC systems, a large, solenoid-type relay is called a **contactor**. The electrical function of relay, solenoid and contactor are pretty much the same; the difference is one of scale. The schematic symbol usually represents the coil by a rectangle, or the coil and the contacts may be represented separately as shown below.



When choosing a relay, solenoid or contactor, pay special attention to whether the coil is AC or DC. A 12VDC relay probably will not work on 12VAC, while a 12VAC relay will burn up if operated on 12VDC.

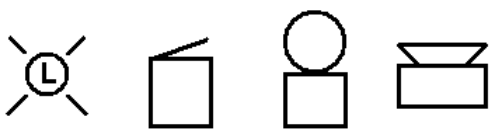
SOLID STATE RELAYS

Today, we have FETs and IGBTs with “on” resistance so low that it's in the same neighborhood as closed switch contacts. Increasingly, these devices are replacing mechanical relays. Relay-equivalents are packaged so they can be used the same way a mechanical relay would be used.

A solid state relay isn't as universal as a mechanical one: you have to pay attention to whether it wants to be activated by AC or DC, and also whether it wants to switch AC or DC. Many solid state relays are based on triacs, and depend on the fact that with AC, the voltage goes to zero twice each cycle. If you try to use them with DC they won't switch off.

INDICATORS AND ALARMS

Machines and systems usually require some form of feedback to the operator so he/she can tell what the machine is doing. Here are schematic symbols for the most common attention-getters: the indicator lamp, the buzzer, the bell, and the horn. These can be AC or DC at any voltage. The lamp symbol may contain an “L” or it may be colored.



lamp buzzer bell horn

Buzzer, bell and horn circuits are the same, and usually take one of two forms. One is essentially a relay with a pair of normally closed contacts. When the relay pulls in, the contacts open, causing the relay to drop out, starting the cycle over. Each time, the armature slaps the pole piece, or in the case of a bell, a striker attached to the armature hits the bell. An alarm horn is just a buzzer with a horn attached to make it louder.

buzzer / bell / horn

The other kind is simply an electromagnet that attracts an armature. The coil is connected to 60Hz AC, and the armature strikes the pole piece 120 times per second.

CIRCUIT PROTECTION

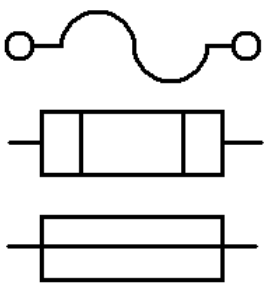
An equipment designer's job is not done until some way has been provided for the equipment to automatically shut itself down if something goes dangerously wrong, because sooner or later, something will. A tech installing a system may have to provide additional shut-down capability for the system beyond what's included in each piece of equipment.

Most faults involve excessive current, so most protection devices are current-limiting or overcurrent-shutdown devices. There are essentially three kinds:

- fuses, used where an overcurrent condition never occurs unless the equipment is broken
- circuit breakers, used where an occasional overcurrent condition is expected
- current-limited power sources, which set a maximum limit to the available current

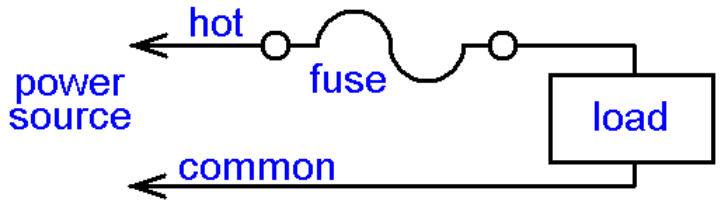
If you're going through all the study guides in order, you've already seen a lot of this information in EM1. But, since that was a while ago, it's time for a review, plus some new information. For each device there are several schematic symbols in widespread use. I'll show you the most common ones.

FUSES



A fuse is one of the simplest of all components – basically an undersized wire. The three most common schematic symbols for a fuse are shown to the right.

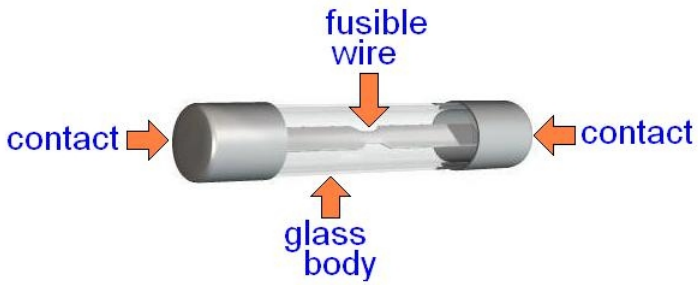
A fuse is wired into a circuit between a power source and load, almost always on the hot side (as opposed to the ground or common side). When too much current flows, the fuse wire melts before anything else in the system can get hot enough to be dangerous. Since it's a piece of wire, and a short piece at that, a fuse has almost zero resistance. There's normally almost no voltage drop across the fuse until its current rating is exceeded. Then it goes open, shutting down the circuit.



In modern fuses, the undersized wire is always enclosed, because there's arcing and metal splatter involved and those things have to be kept away from polite society. We're just going to look at the most common type of fuse used in electronic equipment, the cylindrical **cartridge fuse** that consists of a wire in a glass or ceramic tube with a metal connector cap on each end. Information on some other fuse types can be found in the EM1 study guide, chapter 5.

The traditional fuse sizes are **3AG**, which is about ¼ inch in diameter and 1¼ inch long, and the slightly smaller **8AG** fuse which is ¼ by 1 inch long. European fuses are 5 x 20mm, just under ¼ x 1 inch.

Fuses up to 15A usually have glass bodies. You can tell whether the fuse is blown by looking inside to see if the wire is still intact or melted. Higher-current fuses have ceramic bodies, and then you have to check them by measurement.



("AG" means "automotive glass." These fuses were first used in cars, and the electronic industry borrowed them.)

What blows a fuse is *current*. This confuses a lot of people, because a fuse will usually have a voltage rating stamped on it. That voltage rating tells you the maximum safe voltage of the circuit the fuse is used in, but it is not a factor in whether or under what conditions the fuse will blow. That's a function of current alone.

Fuses are crude devices, and the line between "hold" and "blow" is not precise. They are for use where current during a malfunction would be a whole lot larger than normal current, say 2X or more, so there's an obvious difference between normal current and fault current.

The three most important fuse ratings are maximum current rating, maximum voltage rating, and time.

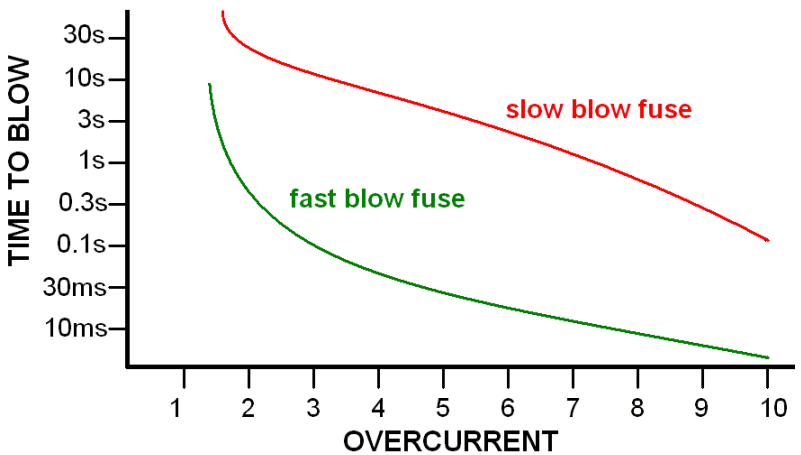
Current – the rated current handling capability, the maximum current at which the fuse will *not* blow. At up to 110% rated current, the fuse is guaranteed to hold. At 135% rated current or more it is guaranteed to blow. When a fuse is tightly enclosed, as in a cartridge fuse holder (see below), the fuse gets hot at a lower current. The fuse's current rating is reduced to 75%; e.g. a 4A fuse becomes a 3A fuse.

Voltage – the highest voltage that can safely appear across the fuse after it blows. There's a momentary arc when it blows, but if the circuit voltage is high enough, it will continue to arc. This creates extremely high temperatures, will probably explode the glass tube, and will continue to feed power to a circuit that was supposed to go dead.

It's important to understand that, when a fuse is blown, the entire supply voltage appears across it. One end is connected to the power source; the other end is connected to the rest of the circuit which is connected to ground or common. So if the unit is plugged into a 120VAC outlet, there's 120VAC across a blown fuse.

It's okay to use a fuse in a circuit that's lower-voltage than it is rated for, e.g. a 250VAC fuse in a 32V circuit.

Time – how fast a fuse blows when it's overloaded. This varies with current; the greater the overload the sooner the fuse blows. It also varies with type of fuse. In the USA, glass and ceramic fuses are either fast-blow or slow-blow. A 2X overload will blow a fast-blow fuse in less than half a second, while a slow-blow fuse may take 20 seconds. A fast-blow fuse is good for protecting electronic equipment. A slow-blow fuse is appropriate with a load such as a motor that draws a very high starting current for a significant time.



The chart above is adapted from information from Littelfuse. Fuses made by other manufacturers have significantly different current-vs.-time characteristics. Again, we're not trying to make fine distinctions; we're talking about a circuit that draws maybe 1A when it's working right and 5A when it's not.

There's a fourth specification, **breaking capacity**, which may or may not be important in a given situation. Breaking capacity tells you how much current a fuse can interrupt. Even if maximum voltage is not exceeded, it's possible for a fuse to continue to arc under some conditions – or, in the case of a glass fuse, the fuse can shatter. Breaking capacity specifies how high short-circuit current can get and still be reliably broken.

A tech does not often have to worry about breaking capacity, but it's handy to know because it's part of a standard developed by the International Electrotechnical Commission, or IEC. The standard lists fuse characteristics in this order:

(1) Letter: time characteristic.

- **T** time delay, roughly equivalent to U.S. "slow blow."
- **TT** very slow blow
- **M** medium blow
- **F** fast blow
- **FF** very fast blow

(2) Number, followed by "A": current. Since "international" usually means "the way they do things in Europe," a decimal point may be indicated by a comma, e.g. "3,5A" means 3.5A.

(3) L, E or H: breaking capacity.

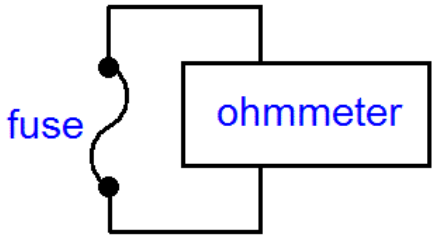
- **L** for low
- **E** for enhanced
- **H** for high. Most glass fuses are L or E. Ceramic fuses, and the big honkin' fuses in AC power panels, are usually H.

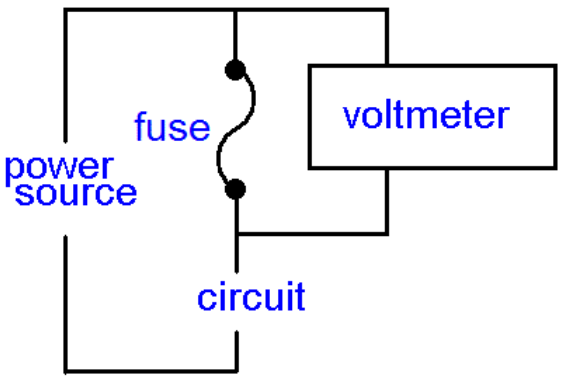
(4) Maximum AC voltage, followed by "V."

So, an IEC-specified fuse labeled "F5,75AL250V" would be a fast-blow, 5.75A, low breaking capacity fuse with a maximum voltage rating of 250VAC. In the USA, most manufacturers either use this system for their part numbers or cross-reference to it. It's handy because you can look at that designation and know everything you need to know about a fuse.

When replacing a fuse, always use one of the correct current and time ratings. A larger fuse defeats the protection; a smaller fuse will just blow again. If you're in the service business, your vehicle should carry every standard fuse size from 1/4A to 10A in fast and slow blow versions. And when you take a fuse out of your supply, replace it when you get back to the shop! A tech who gets to a job site and can't fix a problem because he/she hasn't got the right fuse looks like a fool.

There are two ways of checking a standard fuse. When it's not in a circuit, you can measure its resistance with an ohmmeter. A good fuse has almost zero resistance; a blown one has infinite resistance.



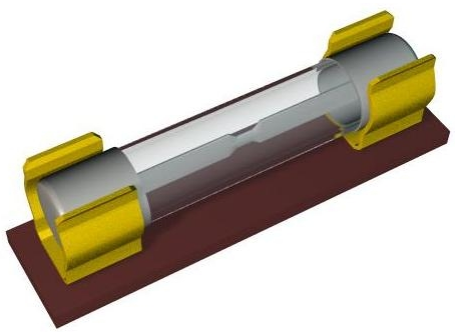


The other method is to leave it in the circuit with power on, and check to see if there's voltage (AC or DC depending on where it is in the circuit) across the fuse. A good fuse should have almost no voltage across it.

Some fuses have indicators. One type has a pin that pops out of the end of the fuse when it blows. If it has the right kind of fuse holder, the pin will touch a contact and current will flow, lighting an indicator lamp.

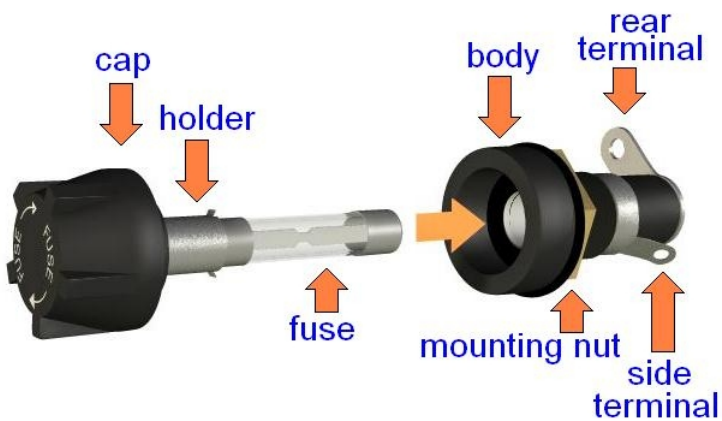
Very-low current fuses, e.g. 1/500A, should not be checked with an ohmmeter. An ohmmeter works by putting a voltage across the probes and measuring the resulting current. This current alone is enough to blow a low-current fuse. The fuse should be checked by measuring the voltage across it when it's installed and the circuit is powered up. If the circuit is the type that, in normal operation, places no voltage across the fuse – for example, an electrical probe in a medical device where the fuse is there to prevent electrocution if the device malfunctions – you'll have no choice but pull the fuse out and measure it with an ohmmeter. Set the ohmmeter to the highest-resistance range.

Fuse Holders



The two most common fuse holder types are the **cartridge** and **clip** holders. Clip holders should only be used where they're totally enclosed inside equipment, unless they're handling voltage levels so low they pose no risk of shock. According to the Electrical Code, that's 50VDC, 30VAC, 12V around water.

A cartridge fuse holder, shown to the right, is safe at higher voltages, and the fuse can be replaced by the user without disconnecting the power. It's intended to be mounted in a hole in a panel, with the electrical connections enclosed where people can't touch them. In most types, the fuse is first pushed into the cap, then inserted into the hole. Then the cap is pushed all the way in and turned to lock.



In a cartridge fuse holder, one terminal is at the rear end and one is on the side. The “hot” side of the circuit, the one that's connected to the power source, should be wired to the end terminal. The “load” side is wired to the side terminal. That way, the fuse doesn't come in contact with the supply voltage until it's all the way inside the holder. If this isn't done – if the “hot” side of the circuit is connected to the side terminal – the fuse becomes electrically hot while most of it is still outside the holder, where a person can touch it.

Some fuse holders have built-in indicators. For example, a fuse holder intended to be used in a 120V circuit may have a neon lamp with series resistor in the cap. The lamp and resistor are wired across the fuse. If the fuse blows, 120V will appear across the holder and the lamp will light.

THERMAL FUSES

A thermal fuse is usually buried deep inside equipment at a point that might get hot if the equipment is overloaded. An example is the windings in a motor. A thermal fuse doesn't blow on overcurrent but overtemperature. It's permanently wired into the circuit and usually not replaceable; once the fuse opens, you throw the whole unit away. In most cases, once a unit gets that hot, it isn't safe to use again anyway.

A very serious drawback of fuses is that, in a 3-phase circuit, one fuse can blow and the others keep conducting. In a 3-phase circuit, we want all three phases on or all three off. One way to avoid this problem is to use ganged circuit breakers as described below.

CIRCUIT BREAKERS

The big difference between fuses and circuit breakers is that the fuse dies a heroic death, while the circuit breaker can be **reset** and continue to function once the overcurrent condition is removed. That's a good thing, because circuit breakers are a lot more expensive than fuses. A breaker doesn't "blow," it **trips**.

We can divide circuit breakers into two types:

- those that need to be reset by hand
- those that reset themselves when the overcurrent condition goes away

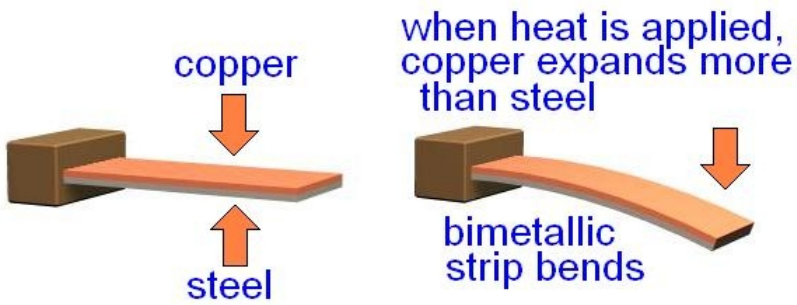
They can also be divided according to their operating principle:

- thermal trip
- magnetic trip
- combination thermal and magnetic trip

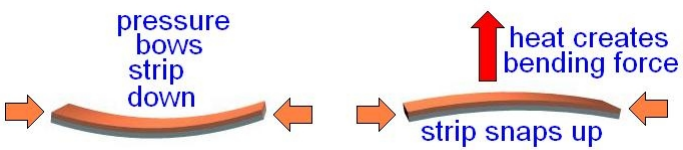
Thermal-Trip Breakers

The mechanism at the heart of most thermal breakers is a **bimetalic strip**, which is two strips of different metals, such as steel and copper, stuck together. The two metals exhibit differing amounts of expansion and contraction as temperature changes.

This bends the strip back and forth as things heat up and cool down.



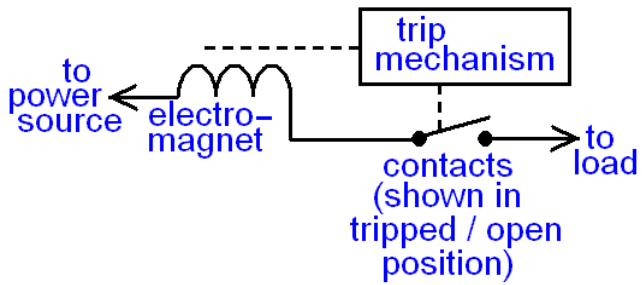
Normally, a bimetallic strip bends gradually as heat increases. But if we squeeze the ends to bow it one way, as heat is applied it will suddenly snap over to the other position, like a can lid popping. Depending on what it's made to do, it will either snap back by itself when it cools off, or it will have to be pushed back via a reset button.



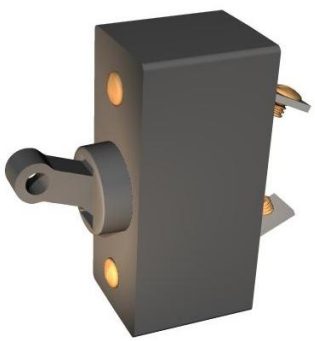
Now all we have to do is add contacts and a case.

Magnetic-Trip Breaker

The main practical difference between a thermal trip and a magnetic trip is that the thermal trip takes a while, but a magnetic trip can occur within thousandths of a second. In a magnetic breaker, an electromagnet is inserted into the circuit. It will have very few turns, maybe 10, of heavy wire, because we don't want it to drop the voltage. We just want it to sample the current on the way through to the load.



Magnetic breakers are almost always manual-reset. Some are even made to go on the front panel of a piece of equipment, with a toggle handle that does double duty as the power switch.



Overtemperature Breaker

There are also thermal breakers that trip when the unit that's being powered gets too hot. One common kind is illustrated on the next page. A bimetal disc is held in close contact with whatever we're measuring the temperature of. The disc is slightly “dished” downwards.

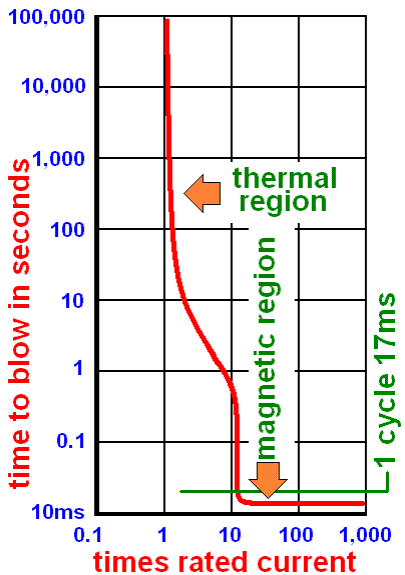
As the disc gets hotter, it tries to bend the other way. At a certain point, it will pop upward like a can lid, pushing on the rod, which pushes the contacts apart. (the illustration is an exploded view.)

These breakers are self-resetting; the dish pops back when it cools off.

Combination Thermal-Magnetic Breaker

When a motor starts, it draws 6 to 10 times as much current as when it's running. For a 1HP, 120V motor, that's up to 80 amps, or a 400% overload on a 20-amp branch circuit. An overload like this is a normal event, and as long as it only lasts a few seconds, it won't cause enough heating of the building wiring to be dangerous. A branch-circuit breaker has to handle it without tripping. That requires a slow-heating thermal breaker characteristic.

But such a slow thermal breaker won't trip quickly on a monstrous overload like a direct short. So breakers in AC distribution panels usually combine thermal and magnetic trip functions.



Here's a chart of the trip characteristics of a circuit breaker typically used to protect the AC wiring in a house. The upper part is essentially a thermal characteristic. The breaker will handle a mild overload for a long time before it trips. Even an 8X overload will take a full second to trip. When the overload exceeds about 12X, the magnetic mechanism kicks in and breaks the circuit in around 12ms, which is less than one 60Hz cycle.

GANGED BREAKERS

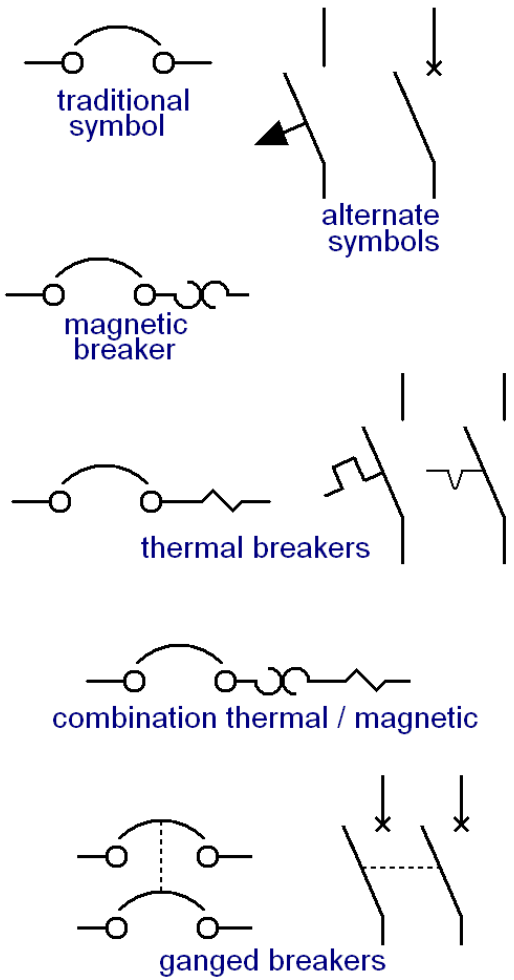
In a case such as a 3-phase circuit, where we would want three breakers to trip at the same time, we can physically **gang** the breakers together. Many breakers are made with holes in the handles to permit a rod to be inserted. In other cases, a single breaker case may have two or three breakers inside.

It's usually easier to turn a breaker off than on. That's because, if breakers are ganged, they have to be easy to trip. That way, the trip mechanism in one breaker can trip up to three at a time.

This is an important safety feature for anyone working on equipment. In the old days, it was considered okay to just break two phases in a 3-phase circuit, and some old buildings are still wired that way. This meant that even after the breakers were shut off, equipment attached to the circuit was electrically hot. The Electrical Code now requires polyphase circuits to have ganged breakers so all phases are disconnected at once. Just to be on the safe side, before you work on installed equipment, take a meter and measure from each phase to ground to be sure the circuit is really dead.

BREAKER SYMBOLS

Each of the traditional types of breaker can be represented by several different symbols, as shown to the right. These symbols are duplicated in the review chapter, which you can print out.



BREAKER OVERRIDE

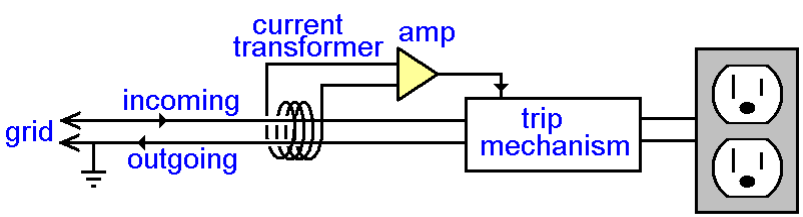
Most breakers are designed so they will trip even if you hold the lever in the “on” position. After all, a trip indicates an overload, which can be a dangerous situation. If a breaker is held on, that defeats its safety function.

However, when a breaker controls an emergency device like a fire pump, shutdown can be even more dangerous. Some breakers are designed with a **manual override**, where the breaker can be held on even in an overload situation.

GROUND-FAULT INTERRUPTER

The ground-fault interrupt breaker or GFI is relatively new, made possible by solid state technology. It is based on the principle that current going out to a load on the “hot” wire should be exactly the same as current coming back on the “neutral” wire. If the two currents are even a little bit different, that means some current is flowing to ground via another path – maybe a person.

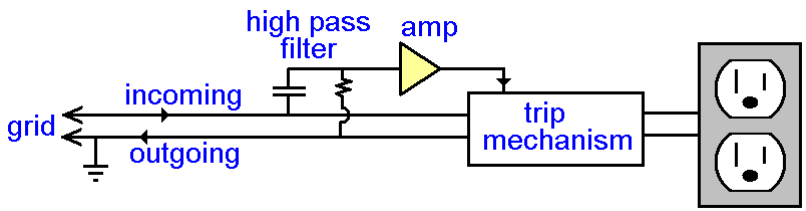
In a GFI, outgoing and incoming wires are passed through a **current transformer**, which is a kind of transformer whose output is proportional to current flowing in the wires going through it. If outgoing and incoming current is the same, the magnetic fields created by the two wires will cancel. If it's not the same, one wire will create a larger field than the other. The transformer and the circuit attached to it will sense this and break the circuit.



GFIs in wet areas or where there are grounds accessible, like kitchens and bathrooms, have eliminated most of the risk of using electricity in a bathroom or damp basement. They can be built into outlets, but they can also be found built into branch-circuit breakers in some AC distribution boxes.

ARC-SENSING BREAKER

Another device that wasn't practical until recently is the arc-sensing breaker. Many buildings have burned down because a bad connection in an appliance, or a fault in the building wiring, has caused an arc that set something on fire. This is so common that some jurisdictions are beginning to require arc-sensing breakers.

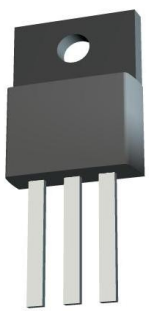


In an arc-sensing breaker, a tap is taken off the wire, a high-pass filter removes the 60Hz, and then the circuit looks for the presence of high frequencies at high energy levels. Arcs generate energy up into the radio-frequency bands. If the breaker sees any of that, it trips.

Unfortunately, I have been unable to find a standard arc-sensing breaker symbol. If there is one, I'm sure some kind soul will send it to me and then the next edition of this study guide will include it. Hint hint.

CURRENT-LIMITED SOURCES

A very effective way of limiting current is to simply design a power source so it can only put out so much current. One of the most familiar examples is the "impedance protected" doorbell transformer. Even a prolonged direct short will not make the wiring, or the transformer itself, hot enough to be dangerous.



Solid-state power supply regulating ICs usually have current limiting built in. For example, the old standby 78XX regulators have a built-in current limit of 0.5A to 1.5A, depending on which particular chip you choose. If you short-circuit the output, the IC will only put its rated current into the short. The IC will heat up, of course, but 78XX ICs also have a built-in overtemperature shutdown.

Electronic equipment like, say, an audio power amplifier is usually current-limited. This is to protect the unit itself, in the case of an improper load, but it also protects the load and the wiring from overcurrent.

Current-limited equipment can save money in an installation. Many Electrical Code rules deal with power-limited wiring, where the power source is so designed that it simply cannot put out enough current to be dangerous. In those cases you can use **class 2** wiring, which in most jurisdictions does not require conduit. Sometimes there is confusion when two or more sections of the electrical Code governing a particular situation give conflicting rules. Look at the equipment itself; often, the correct wiring method is printed on the case.

End of chapter 6

EM5 chapter 7
INTERFACING ELECTRONIC PRODUCTS: LEVELS AND IMPEDANCES

Objectives of this chapter:

- *describe single ended / unbalanced signals and differential / balanced signals*
- *describe the causes of ground-related problems and how various systems cope with them*
- *list various audio, video, RF and data levels and impedances*
- *explain when impedance matching is and is not necessary, and the consequences of not matching impedances when they should be*
- *define "transmission line" and explain how to tell whether a cable is a transmission line or just wires with voltage on them*
- *explain how units with unequal impedances can be matched*
- *discuss reference levels, actual levels, and headroom*
- *discuss AVC and AGC*
- *describe the symptoms of signal conflict*

In this chapter and the next, we're going to talk about connecting up different pieces of equipment. There is one more chapter after these two, which deals with non-technical issues, and then the EM study guides dealing with wired signals will be complete. (There is still one more module, EM6, dealing with wireless systems.) So in these two chapters, besides talking about interconnects, I'm also going to review and summarize topics from the EM1 thru EM4 study guides that have to do with interfacing electronic products. There are 8.27 kazillion different ways to connect things, so I've just chosen a sampling of the ones you'll run into most often.

You can't just take any old kind of wire and any kind of connectors and make up an interconnection system that will work. You need to know the electrical characteristics of the following:

- the signal source
- the signal destination (what it's being fed to)
- the transmission path (shielded cable, unshielded cable, air, space etc)
- the signal itself

There are physical, practical and financial constraints on all these factors. When a new communication method is invented, engineers create a signal standard that they think represents the best balance of technical quality and real-world practicality.

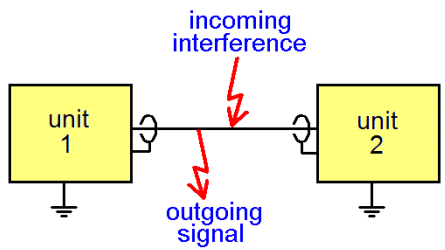
As you study the electronic standards in this chapter and the mechanical ones in the next, you will see evidence of this balancing act. We need to go through this discussion before we actually look at the signals, because it's useful for a tech to understand what the designers were trying to achieve, and what they were trying to avoid. For one thing, this knowledge is helpful when a system isn't working quite right and you're trying to find out why. A tech who knows a type of signal well can often form a mental picture in moments of what's happening and where a problem lies.

Let's take a closer look at the factors listed above, in reverse order just because this is my show and I can be nerky if I want.

SIGNAL CHARACTERISTICS

The following issues, at least, have to be decided:

- Is the signal going to be defined as a voltage,current or power level? A signal has all of these, but we have to decide which one we're going to measure by. For example, a loudspeaker converts electrical power into sound power. Since we're dealing with power, it wouldn't make sense to specify the output of a speaker-driving amplifier in volts or amperes. We specify it in watts.
- Approximately what signal strength are we talking about? For example, if a certain kind of amplifier typically runs off a 12VDC power supply, it wouldn't be a good idea to choose a “normal” signal level of 35VAC, unless we actually need that voltage, because creating a 35VAC signal with a 12VDC power supply is a bit complicated. On the other hand, one particular digital standard requires much higher voltages than what computers run on nowadays, and for good reason.
- What is the impedance going to be? At low frequencies, it often doesn't matter much, but at high frequencies it becomes a critical issue. Some impedance ranges are more practical than others, and once a standard impedance is chosen, every piece of equipment must be designed to fit it.
- Cables pick up unwanted noise from the environment, and radiate their own signals. Would this cause problems in a given situation, and if so, how do we deal with it?



- What is the signal's frequency or frequency range?
- If the signal is encoded in some way, what's the coding scheme?

TRANSMISSION PATH CHARACTERISTICS

As a signal moves along the path from the output of one unit to the input of another, it always suffers some degree of damage. The signal should be designed so it's hard to damage, and the transmission path should be designed so it doesn't cause more damage than necessary.

A few things that have to be taken into account:

- A signal gets weaker as it moves from one place to another. That's called **attenuation**. In the case of a wireless signal, attenuation is usually huge. An FM radio's antenna may only get 3 femtowatts, 3×10^{-15}W, from a distant station transmitting 100,000 watts. That's an attenuation of 30 quintillion to one. ($3 \times 10^{20} : 1$)
- Cables attenuate high frequencies more than low frequencies. If a signal contains energy over a wide frequency band, as most digital signals do, the cable affects some parts of the signal more than others .
- If the signal follows multiple paths between the transmitting unit and the receiving unit, or if it bounces back and forth a bit, it will arrive at the receiving unit more than once. This may lead to distortion or data corruption, or the signal may cancel itself, leaving the receiver with nothing to work with.
- As mentioned, a signal moving along a transmission path can both radiate outward, and pick up incoming interference.

SIGNAL SOURCE AND DESTINATION EQUIPMENT

Some signal and transmission characteristics are governed by physical factors we can't change, so equipment just has to be designed however it needs to be to work within those constraints. On the other hand, there are some factors where we have choices, and we optimize those so the equipment can be as small, simple, un-quirky, easy to work with and inexpensive as possible.

Again, everything is a balancing act among cost, practicality and performance. Interfaces are not designed to work as well or reliably as they could, that would cost too much. They are designed to work just reliably enough, and perform just well enough, to meet the needs of the application. They walk the line between “OK” and “not OK” all the time, especially with very high speed data and simple transmission media like unshielded twisted pairs.

Offhand, I can think of four things this should say to a tech:

1. When designing a system, don't push the limits. If you do, the system may work fine, but if it doesn't, you'll have to do an expensive on-site rework, and you look like a clown in front of your customer. Leave some margin.

2. When you're called in to fix somebody else's screwup, keep in mind that even if you can't find anything obviously wrong, something like an overly long, low-quality cable might be pushing the operation just a bit outside working limits.
3. Always use the correct cables and connectors.
4. If possible, assemble the whole system in the shop and test it before you take it to the jobsite, using the actual cables and parts you're going to install.

Before we get to signal types on page 10, here are some required knowledge items to file away in your brain.

IMPEDANCE

Impedances matter. If you've gone through all the EM study guides in order, you know why, and you can skip this topic. But some people go for the EM5 certification alone, so here's a summary.

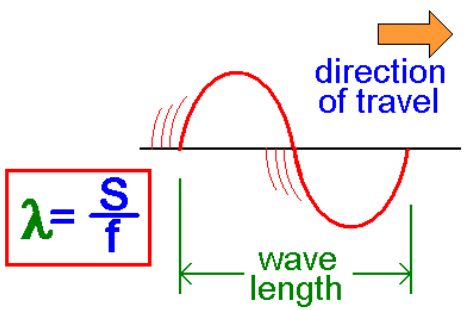
Quick review: **impedance** is resistance that may not be purely resistive. It may have a little inductance and / or capacitance in it, which will throw voltage and current out of step with each other. Mathematically, impedance is the algebraic sum of resistance, capacitive reactance and inductive reactance. All those quantities are measured in Ohms, so we can come up with a single number for impedance at a given frequency. Equipment is designed so the tech doesn't have to bother with the details, beyond saying “impedance” instead of “resistance.”

TRANSMISSION LINES

Since there is no connection between the wires in a cable, you'd think that a cable's impedance would be about infinite (open circuit). That's true for short cables and low frequencies.

But when a cable gets long enough that its length begins to be comparable to the wavelength of the signal it's carrying, it becomes a **transmission line**, and then the physical relationships among various parts of the cable create a specific impedance.

The wavelength of a signal, the physical distance in air, space or cable between the leading edge and trailing edge of a wave, is the speed with which it is moving, divided by the frequency. The symbol for wavelength is the Greek lowercase Lambda, λ.

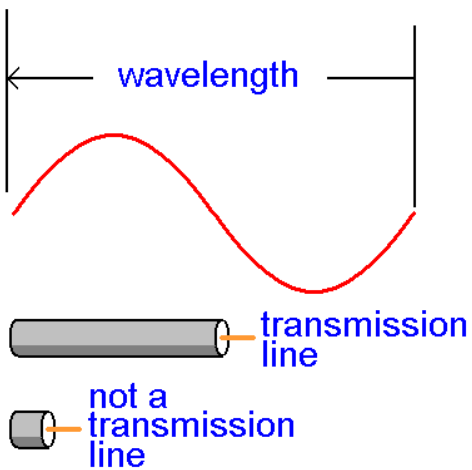


In air and space, speed of an electrical signal is 3×10^8 meters / second. So, a frequency of 100MHz, 10^8 Hz, would have a wavelength λ of:

$$\frac{3 \times 10^8 \text{ M/S}}{10^8 \text{ Hz}} = 3 \text{ meters}$$

...or about 10 feet. In a cable the speed is a bit slower, but we still use the 3×10^8 figure unless there is a need to be precise.

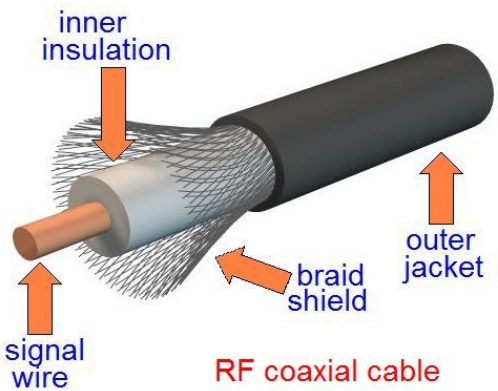
A cable begins to act like a transmission line when its length is 10% of the wavelength. Thus, if a wave at 100MHz is 3 meters long, we should treat a cable longer than 0.3 meter, one foot, as a transmission line.



Certain impedance ranges result in cables that are physically impossible or impractical. So the tail winds up wagging the dog: an impedance is chosen that will result in a workable real-world cable design.

Cables you'll be working with:

- Audio cables don't have an “impedance” because, at those low frequencies, the wavelengths are too long for typical cables to become transmission lines.
- Coaxial video cables have a 75Ω impedance.
- All other coaxial RF cables, with few exceptions, have a 50Ω impedance.

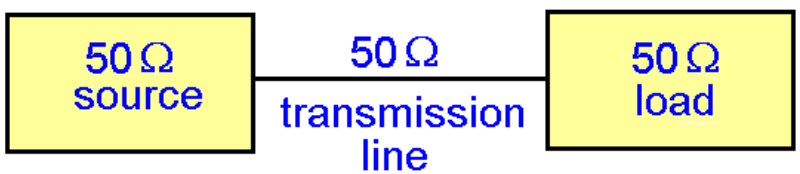


- **Twinax**, which is a type of shielded pair used for high speed data transmission, is 110Ω.
- Twisted pair cable can have any impedance. The type used in CAT5 and CAT6 has an impedance of about 100Ω.
- Flat video / FM **twinlead** has a 300Ω impedance.

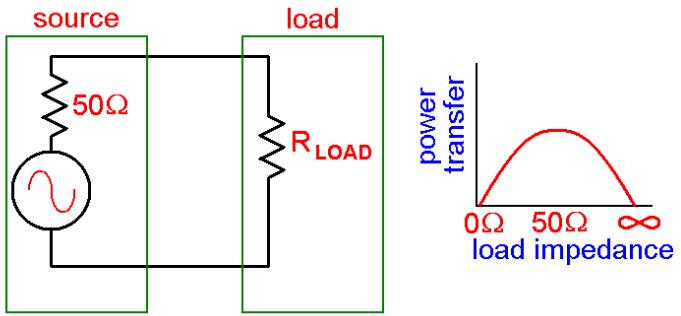
Under normal conditions, we don't think of 60Hz AC power as having a specific impedance. With extremely long lines, hundreds of miles long, impedance effects do appear. This is a topic for AC power grid specialists and we won't cover it here.

MATCHING IMPEDANCES

There's a widespread belief – I'd call it a superstition – that impedances must always be matched; that is, the signal source, the load, and the cable that connects them must always have the same impedance, and if you don't do that, Ben Franklin will come back to life, attach a lightning rod to your head, and push you out into a thunderstorm.

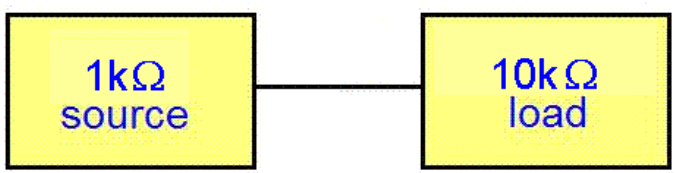


The "rule" that impedances must be matched is usually right, but you should know when it is, when it's not, and why. The reason usually given is is that the maximum amount of power is transferred from the signal source to the load when the two are the same impedance. As shown in the illustration above right, power transfer is least (zero) into a short or open circuit, and greatest when the load impedance is the same as the source impedance.

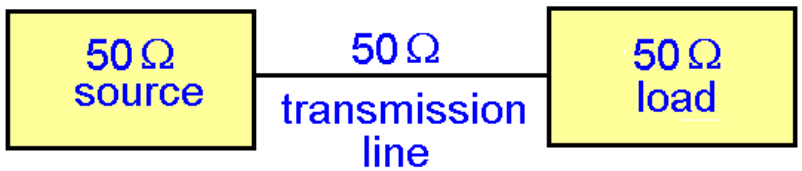


Maximum power transfer is an issue where the signal is very weak, as it was in the early telephone days when the rule was developed. Before amplifiers, all the signal you had to work with was the signal generated by the telephone mouthpiece, and you had to make sure as much of it got used as possible.

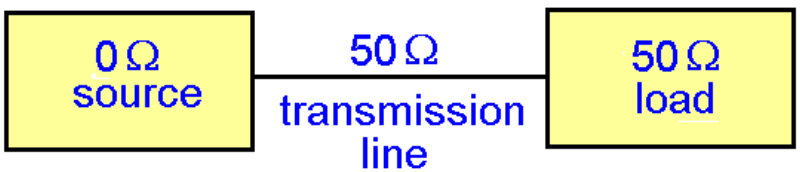
But now that we have amplifiers, that problem is history. When a signal is weak, as when an antenna is picking up a distant station, we can boost it. And even then, loading the signal lightly – connecting a 1kΩ source to a 10kΩ load, for example – often improves the signal-to-noise ratio.



On the sending end, efficiency is usually more important than maximum power transfer, especially these days when so many things are run on batteries. In a classic matched system, half the power generated by the signal source is burned up in its own internal impedance. For best efficiency, source impedance should be much lower than the load impedance.

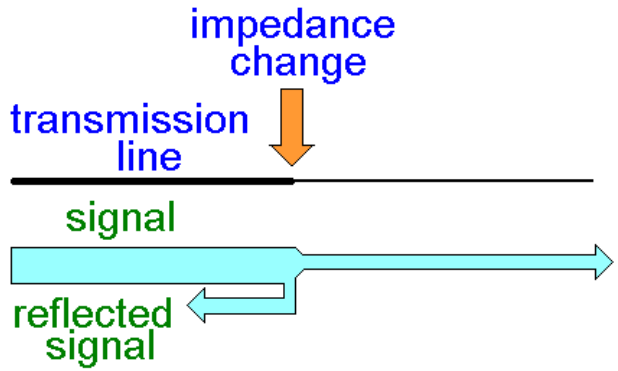


maximum possible efficiency = 50%



maximum possible efficiency = 100%

So, if both noise performance and efficiency are better if we don't match impedances, why would anyone do it? The real reason to match impedances is that, when a signal is moving along a transmission line and encounters an impedance change, part of the signal will be bounced back or **reflected** toward the source. Less signal gets to where it's supposed to be going. And if the source is also a different impedance from the cable – for example, if it's designed for high efficiency and has a low output impedance – the signal will be reflected forward again, but delayed.



In an analog system, this degrades the signal. In a digital system, it can cause data errors. In a high-powered RF system, it can damage the equipment.

Any physical change in a transmission medium will cause signal to be reflected. Where cables must be joined, the way to minimize reflections is to join cables using connectors designed for high frequencies, having the same impedance as the cable. We will discuss that in the next chapter.

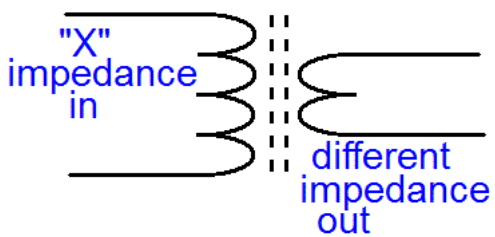
When the signal reaches the receiving end, the equipment it's connected to must also have the same impedance as the cable. Then the signal is properly welcomed, checked in, and given the keys to its room, rather than being thrown back into the street.

When a transmission line is connected to a load of its own impedance, we say the line is correctly **terminated**.

IMPEDANCE CONVERSION

It is often necessary to connect units with different impedances. This can be done by inserting a resistor network in the signal path, but resistor networks always attenuate the signal. (This is called **insertion loss** , the loss caused by inserting the network into the signal path, and is typically at least 6dB, or a 2:1 voltage loss.)

The most efficient impedance conversion device is the transformer, which in theory can have zero loss. One very common application: an FM antenna's output is typically 300Ω balanced. If it's a long way from the receiver, it's best for the connecting cable to be coax to avoid interference. This requires conversion from 300Ω balanced to 50Ω unbalanced. The transformer that makes this conversion is called a **balun**.



(You may be wondering why there's no 300Ω coax. A coax's impedance is determined by the ratio of the signal wire's diameter to the shield's diameter. The dimensions become impractical above about 150Ω.)

GROUNDING

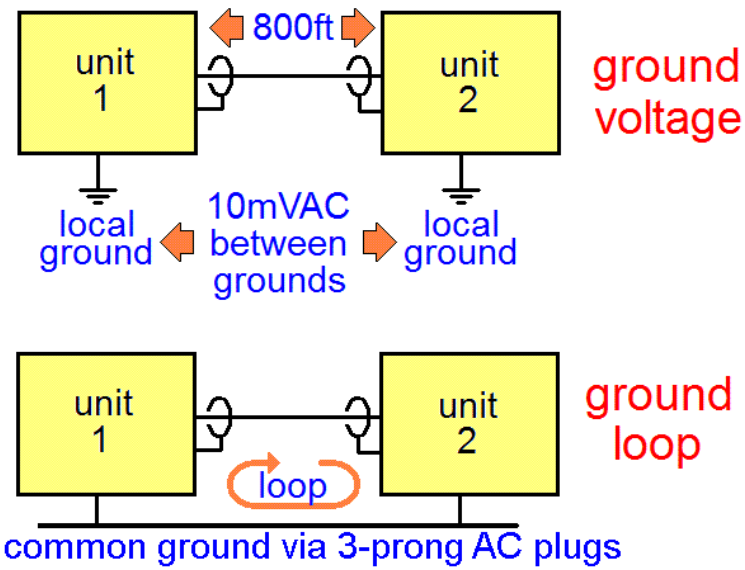
Way back in EM1, we talked about the fact that we're usually dealing with an electrical potential, which is a voltage difference across two points, and that one of those points is often chosen to represent a “zero volt” reference called “ground.” In EM2 and EM3, we talked about the problems caused by grounds that are supposed to be at the

same voltage but aren't, and how that is dealt with. We talked about circuit, chassis and Earth grounds, and saw that cable shields should almost always be connected to chassis grounds.

(Look how far you've come: I just compressed fairly advanced material from several study guides into three sentences and you understood what I was talking about.)

To recap: equipment interconnections involve ground-related problems primarily because two connected pieces of equipment may be located far apart, so there may be a voltage between their ground points, or because they may be connected together via several ground paths, leading to ground loops and inductive interference pickup. In both cases the problem is the same: the sending unit (unit 1 in the illustration to the right) references the signal it's putting out to its own ground, while the receiving unit (unit 2) measures the incoming signal against its own ground. If there's an AC voltage between the two grounds, either because of a ground potential difference, or because a ground loop induces an AC voltage between the ends of the shield, that stray AC gets added to the signal, which is uncool.

The interconnect designs we're going to study take various approaches to this problem. Only one completely solves it, and that one is tied to a 31.25kHz data rate, which isn't very fast.



In the diagram above, note the broken ovals around the signal wire. This is a standard way of showing a shielded wire in a diagram. The shield is actually continuous, surrounding the signal wire all the way from unit 1 to unit 2. The chassis grounds of the two units are connected together via this cable shield.

The others make half-hearted attempts to deal with the issue, meaning they usually work but sometimes don't. A tech who gets good at smoking out ground-related problems is regarded as a special kind of expert.

(Maybe “smoke” isn't a good word to use when talking about electronic equipment. Might be a jinx.)

So now, finally, after 9+ pages of prep work, here we are, ready to talk about actual signals.

AUDIO SIGNALS

Even if you don't think your career path will involve audio, pay close attention to this section. Audio came first and everything that came later borrowed ideas from it.

The main thing about audio signals that's different from most others is that the frequencies are low enough, thus wavelengths long enough, that cables are not transmission lines. Thus there's no reason to match impedances. Typically, an audio output has a fairly low impedance and is connected to a load of much higher impedance; that is, an output acts as a lightly loaded **stiff voltage source**. This is true even when an impedance is specified. For example, a power amplifier may have an “8 Ohm” output. This means it is designed to drive an 8-ohm speaker. Its actual output impedance may be 0.01 ohm.

The other thing about audio is that levels vary all over the place. The difference between a whisper and a shout is a voltage ratio of 1,000:1 and a power ratio of a million to 1. This span is called the **dynamic range** of the sound.

We deal with this by choosing a **reference level** that represents “full volume,” the loudest moments of whatever sound we're dealing with, on the assumption that if equipment can handle this maximum level, it will also be able to handle any lower level. Then we compare other sounds to that reference level using decibels.

A full decibel discussion would double the size of this chapter, and if you've gone thru the EM3 study guide you've already done decibels. But everybody has seen “VU” meters with a “0” about $^{2}/_{3}$ of the way up the scale, a black part below that represents levels lower than “0” and a red part above that represents levels higher than “0.” You adjust the knobs so the loudest parts of the signal peak at “0” on the meter. When people talk about “reference levels” in audio, they're usually referring to this kind of “full volume” level.

“VU” stands for **volume unit**. It's a reference that implies both level and ballistic (i.e. time response) characteristics.

VU meters are not as important as they once were, but the concept is still useful: a level, labeled “0,” that represents a short-term average of the loudest moments, a reference that other levels may be compared against. This “reference level” idea is found throughout electronics.

Something else that's found throughout electronics: the *reference* level isn't always the same as the *actual* level normally found in use. We'll run into that right away.

Audio Line Level & Impedance

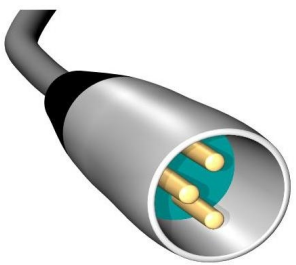
Line level is the signal level used for distribution within an audio system. If you have an MP3 player plugged into a mixer, and the mixer plugged into a graphic equalizer, and the graphic equalizer plugged into a power amp, the signals in those cables are line level. The term “line” is a holdover from the first big use of audio, the telephone system.

There are two common types of audio line level, one for professional equipment and one for consumer equipment.

Professional audio technology was imported from telephone technology. The standard format in telephone work is 600Ω (occasionally 900Ω), balanced. So 600Ω became the standard pro audio impedance, and impedances were matched throughout the system. The standard reference level was established as 1mW, which in a 600Ω circuit works out to a voltage of about 0.78V. This is called **0dBm**, zero dB referenced to 1 milliwatt. A higher level would be “plus X dBm,” e.g. +6dBm; a lower level would be “minus x dBm,” as in -10dBm.

Impedances are no longer matched in modern audio systems. The actual impedance of a pro-audio line level output is usually 50Ω or lower. The load impedance is 600Ω or higher. In this situation, a power-based reference no longer makes sense. So now pro audio people use the same level, but they tie it to voltage instead of power. 0.78V is the pro audio reference level, and it's abbreviated **0dBu**.

The *actual* level that appears at an output and reads “0” on a VU meter is 4dB hotter, i.e. **0VU = +4dBu**. That's about 1.23V. Audio techs call this “plus four.”



Whenever you see a 3-pin XLR plug or jack used as a line level connector, you can be pretty sure you're dealing with a professional-standard signal.

Consumer audio technology is based on lower levels, higher impedances, and unbalanced lines. The standard level is one volt, **0dBV**. The actual level is about 0.32V, -10dBV. Again, these correspond to the loudest moments. Quieter sounds correspond to lower voltages.

A consumer-type output typically has an impedance of 100Ω to 1kΩ. An input will be 5kΩ or higher, often much higher. An RCA connector automatically means consumer line level.

Exception: a magnetic phonograph pickup is usually connected by RCA plugs, but the level, impedance and equalization are special. It can only be plugged into an input specially designed for it, and an input designed for a magnetic phonograph pickup won't work with any other kind of signal. Not all “phono” inputs are for magnetic pickups; it depends on the specific equipment. Now that phonographs are rare, you're not likely to run into this unless you deal with this specific kind of audio.

A ¼” phone plug may carry either a pro or consumer type signal. Check the user manual.

A lot of audio equipment these days is “prosumer,” with consumer-type line inputs and patch connections for equalizers etc, and pro-type main outputs. They can be interconnected, but the levels will not match and you'll have to set the controls to weird positions.

Telephone Line Level & Impedance

Telephone lines are a special case in audio. Because land lines are often many miles long, they do act as transmission lines and so must be properly terminated. Because signal goes both ways, both ends must be terminated. The standard impedance is 600Ω. (900Ω is also used.)

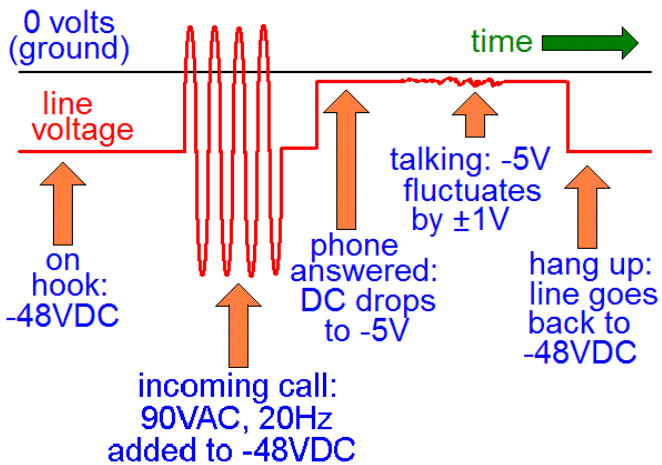
In a way, the U.S. telephone system is a victim of its own early success. Signal and wiring standards were established nearly a century ago, and we've never been able to make a complete break from them because the telephone system evolves piece by piece and new parts always have to work with old parts. You can still connect a 1930s candlestick telephone to a land line and it will work.

“Plain old telephone service” (POTS)

This is the land line telephone system that has existed for almost a century. It has the following characteristics.

- Wiring: unshielded twisted pairs called **lines**. Lines are balanced or pseudo-balanced, which is explained in the EM3 study guide.

- On-hook voltage: when the phone is “on hook” (not picked up) there is 48VDC across the pair. One wire is at ground potential (but not grounded – it's balanced, remember) and the other wire is at -48VDC. When a call comes in, a 90VAC, 20Hz sinewave is superimposed on the 48VDC to ring the bell. The word “hook” is a holdover from the candlestick telephone days.

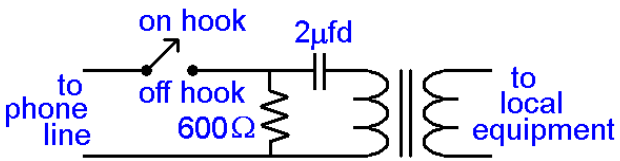


- Off-hook voltage: when the phone is “off hook” (picked up) the phone loads the line. DC voltage drops to around 5V. This voltage powers the transmitter (microphone) and whatever other circuitry is in the phone. In telephone work we measure signal power, not signal voltage. The reference level is 0dBm, one milliwatt, which is about 0.78V in a 600Ω system. That is also close to the actual level when someone is speaking loudly. The signal is filtered to limit the frequency band transmitted to a range of about 300Hz to about 3.5kHz.

FYI – in early phone systems, the wire with voltage on it was positive, like today's cars and most electronic stuff. Engineers discovered that outdoors, this caused wires to be eaten away by electrolysis, so they switched the polarity. A negative voltage with respect to ground actually protects the wires. This is called **cathodic protection**. Lots of cases in electricity and electronics where it's useful to know that.

When connecting into a telephone land line, the following precautions must be observed.

1. The line must be isolated from local equipment, i.e. there must be no direct AC or DC connection. This calls for an isolation transformer.
2. If it's just a line provided for an audio link, the transformer can connect directly to the line. However, if it's a standard land line with DC on it, a 2mfd capacitor should be inserted to keep DC from going thru the transformer. A separate resistor across the line provides a current path to “pick up” the line and match its impedance. The illustration on the next page shows a typical circuit for feeding a signal from a phone line into local equipment, as would be used in a paging system. This is called a **voice coupler**.



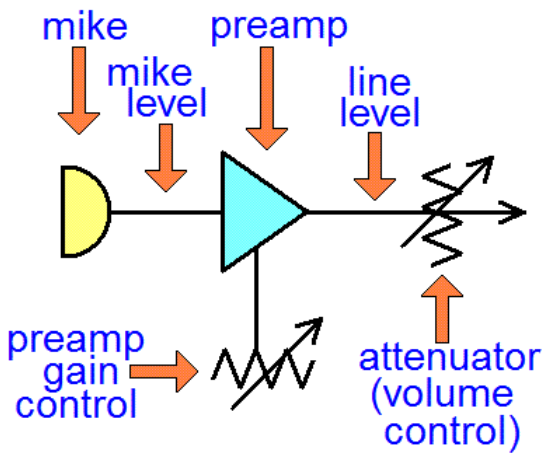
3. If you're feeding a signal into the line, it must be limited to about 1 volt AC. If it's much stronger, it may leak into other people's conversations.
4. Unless you've been given a special line, don't try to use equalization to force a wider response than 300-3.5kHz. Those limits are necessary for reasons that are beyond the scope of this study guide.
5. Whether sending or receiving, the line must "see" a matching 600Ω (sometimes 900Ω) impedance.

If you fail to observe these rules, and screw things up for the phone company, they have the authority to terminate your service and may have authority to confiscate your phone equipment.

Microphone Level & Impedance

The voltage coming out of a microphone is usually much lower than line level – a few millivolts when someone is speaking into the mike in a normal voice. With extremely loud sounds, e.g. when a mike is placed inside a kick drum, the voltage may reach line level. In the diagram above right, note the symbols for microphone, amplifier and attenuator.

These are the most common block-diagram symbols for those components.

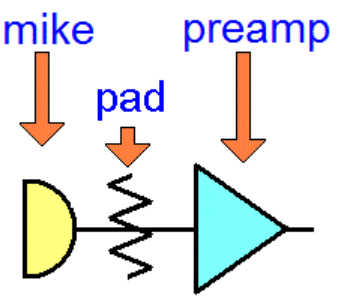


Microphones (mikes for short, or mics) must be connected to special inputs which are designed for them. From there they are routed to **preamplifiers** which boost their signal to line level. In a system with microphones, the preamps come before the volume controls in the signal chain. Volume controls are called "gain" controls, but they are actually loss controls; they attenuate. For most volume controls, output is equal to input when the knob is all the way up, and at all other settings output is lower than input. Electrically, a standard volume control circuit is simply a variable voltage divider.

Since a microphone's signal level is already very low, if the signal is further attenuated it may be lost in the background noise (hiss) that's always present. That's why it's preamplified before it gets to the volume control.

This means, if the signal from a mic is unusually hot, the preamp may overload. Turning down the volume control won't fix the problem, since the signal has been ruined by the time it gets to that point in the circuit. A higher quality audio preamp may include a gain control, as shown in the previous illustration, which is used to preset the gain so it's in the general range needed.

If a preamp doesn't have a gain control, a hot mic signal can be tamed by inserting an attenuator ahead of the preamp. For a low-level signal, that would cause an increase in background noise. Then again, when the level is hot enough to require an attenuator, background noise is not an issue.



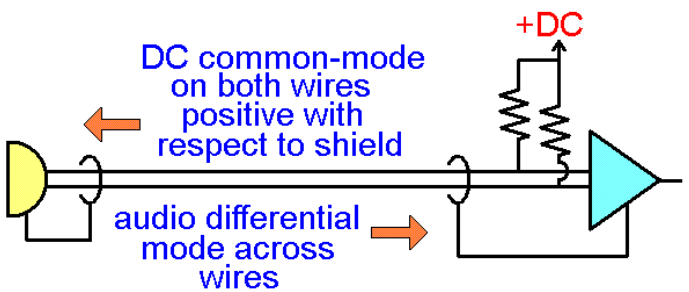
An inline attenuator is often called a **pad**. If you wind up working in the music business, be aware that to a musician or producer, “pad” means something else: a background track where a bunch of symphony-level violinists play long notes and try to avoid falling asleep.

(Pads also show up elsewhere in electronics, e.g. adjusting the signal level in a video or cable internet system.)

High-impedance (50kΩ) microphones were common in the tube days, but no self-respecting tech would use them now.

The standard impedance is low (150 to 600 ohms) and a mic line is usually balanced. A mic should be lightly loaded, so a preamp input is usually 1kΩ to 5kΩ. Paging amplifiers often have actual 150Ω inputs, which messes up the mics' frequency response, but with paging, nobody seems to care.

A **Condenser** mic has what might be called a pre-preamp built into it which needs a DC power source. This is almost always supplied as a **phantom** DC voltage on the signal wires. The voltage varies widely, from about +6V up to +48V. That's a ridiculous voltage for a microphone, but there's an historical reason. Long story.



In a phantom-powered condenser mic, the DC voltage is fed from the input to the microphone and the sound is fed from microphone to input on the same wires. The DC voltage is common-mode (same on both wires) and is connected between the signal wires and the shield. The audio is differential-mode (balanced) across the signal wires.

The best interference rejection is obtained when a balanced pair has no connection to a ground at either end. This is called a **floating** circuit. Professional dynamic and ribbon mics are floating, but a phantom-powered condenser mic cannot be, because there's a DC circuit through the shield. On the other hand, condenser mics have up to 10dB higher output, so that partially compensates.

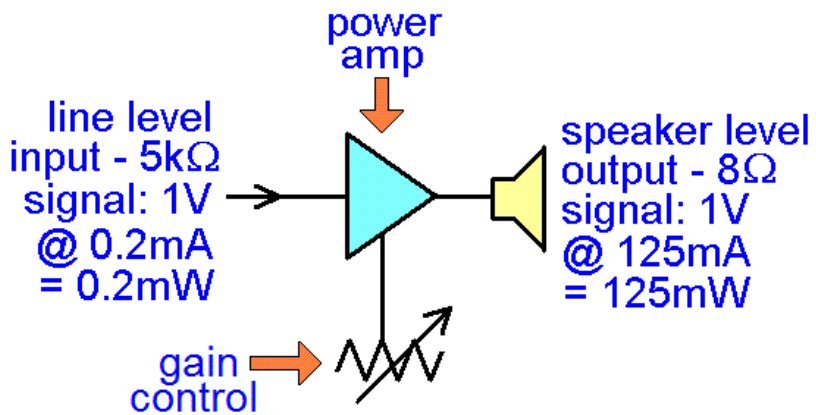
There is one common exception to the above rules: condenser mics intended to be tethered to wireless belt packs are unbalanced and have an impedance of several kilohms.

Speaker Level & Impedance

For background music, the voltage coming out of a power amplifier may be about the same as line level, a fraction of a volt. But a power amp puts out a lot more current than a line output, because speaker impedance is much lower than for a line level load, so the power level is much higher. Do the math, it'll make sense. The illustration to the right shows a case like that.

Very loud music may correspond to an average voltage of 30V. Again, do the math: that's a bit over 100W into an 8Ω speaker.

The standard speaker load impedance has been 8Ω for many decades. Some amplifiers are designed to drive 4Ω, even 2Ω loads. This permits the user to connect two or four speakers in parallel. The amplifier's actual output impedance is often in the hundredths of one ohm – it's the stiffest of "stiff" outputs – but if you try to drive a load of that impedance the amp will shut down or blow up.



Contrary to popular belief, an audio power amp does not have to be loaded. It will work happily into any load between its specified load and an open circuit. Of course, since it's a stiff voltage output, the higher-impedance the load, the less power developed. Do the math. I mean it, you need the practice.

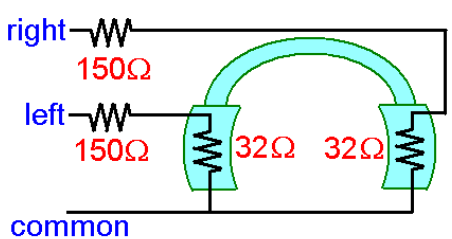
70V Speaker Systems

There's a special class of system where the speaker load is typically not the familiar 8Ω or 4Ω. This is called the “70V” system (sometimes 25, 100 or 140V), or the “constant voltage” system, which is a ridiculous name because audio levels aren't constant except for test signals.

I won't go into it here because it's a specialty. The takeaway for the moment is, if you're working on an installed system in a large building, don't assume you can get an extra speaker from Best Buy and connect it into the speaker wiring. The levels and impedances are totally different, it's like plugging a 12V car radio into a 120V wall outlet. You may blow everything up.

Headphone Level

The voltage needed to drive a headphone to an almost hearing-damaging level is about the same as consumer line level, about 0.3V. However, the current is much higher because headphones are typically 32Ω. When headphones are driven off a speaker output, as they often are, series resistors are used to cut the voltage down.



AUDIO LEVELS SUMMARY

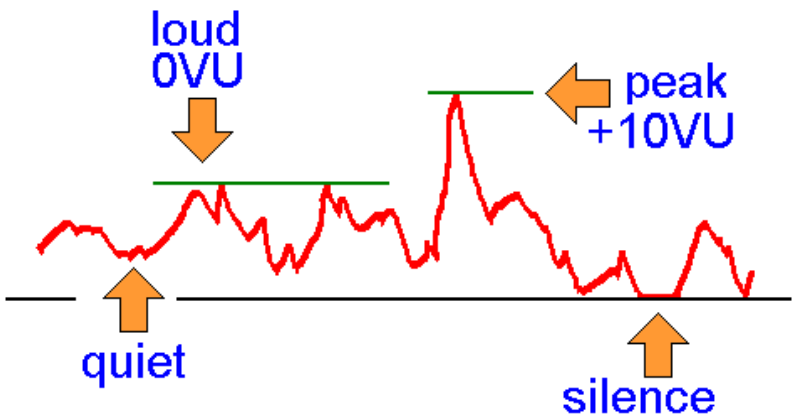
TYPE	REFERENCE	ACTUAL
Line, professional	0dBu, 0.78V	+4dBu, 1.23V
Line, consumer	0dBv, 1V	-10dBV, 0.32V
Microphone		1mV typical
Speaker		1V-30V typical
Headphone		0.32V typical
Telephone	0dBm, 1mW	0dBm
0VU	identifies “maximum short-term average” level. In professional work, 0VU usually = +4dBu	

AUDIO IMPEDANCES SUMMARY

TYPE	TYPICAL OUTPUT	TYPICAL INPUT
Line, professional	50Ω	600Ω & up
Line, consumer	300Ω	5kΩ & up
Microphone	150 or 600Ω	1-5kΩ
Microphone, belt pack	5kΩ	10kΩ
Speaker	0.01Ω	8Ω
Headphone	10-100Ω	32Ω
Telephone	600Ω	600Ω

HEADROOM

Audio contains short-duration (e.g. 1mS) peaks at least 10dB above the average level, which come and go too fast for the old mechanical VU meter to respond to. This means the real maximum level is at least 10X the average power or 3X the average voltage. Thus, if you want undistorted sound, you can't run a 100W amp harder than about 10W average. If you're a golden-eared audiophile and you never, ever want to hear clipping, a 15 to 20dB margin is better.



The name for that extra margin is **headroom**, the difference between maximum normal level and the absolute level limit of the system. If the level goes higher, the signal peaks will be sheared off. That's called **clipping**.

AVC

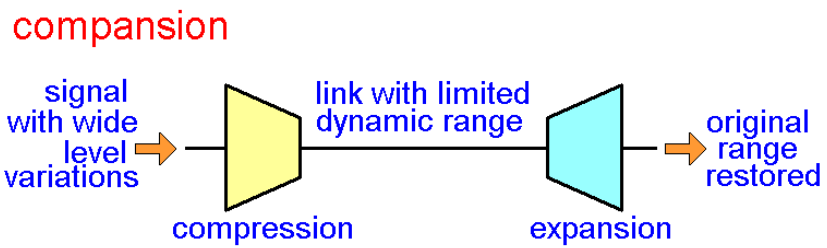
In radio, the hard limit is 100% modulation. (Something to look forward to studying in EM6.) Anything over that, and the signal will splatter over into another station's channel. In the early days, that meant whenever someone was talking on the air, an engineer was legally required to keep one hand on the volume control at all times, and make constant adjustments so the level would be as high as possible, but not exceed the limit. Audio techs call this **gain riding**.

Eventually, equipment was developed to handle this chore automatically (and better than a human, because it can respond to an excessive level much faster.) In audio, this is called **automatic volume control** or **AVC**.

Radio stations play a kind of game. There's a rule of thumb that says, as people tune around among stations, they will be most drawn to whichever station is loudest. Since there's an absolute 100% limit, the only way for a station to be loud is to get as close to that limit as possible. That means, every time a peak comes along, the AVC must momentarily turn down the gain. You've probably noticed songs where every drumbeat punches a hole in the vocals. That's AVC at work. I think it sounds awful, but then I'm an old geezer who likes to listen to pipe organs, so I'm strange.

In audio, using an AVC unit to reduce level variations is called **compression**...not to be confused with digital data compression, which is something different. (See EM4.)

The original loudness range can be restored by sending the signal through another unit that stretches out the signal levels again. This is called **expansion**. The complete compression-expansion process is called **companion**. It's used when a signal has to be sent through a system whose dynamic range isn't as wide as we'd like. An especially refined companion system is what built the Dolby company.

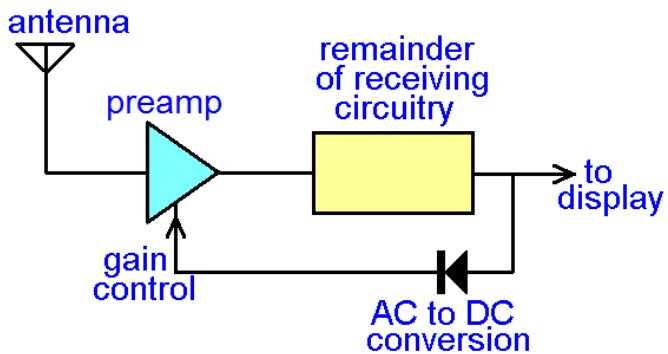


AGC and WIRELESS

There are a zillion places outside audio where we want to ride gain automatically. The more general term for AVC is **AGC**, or **automatic gain control**.

Where AGC is used most today is in wireless systems, like AM and FM radio, TV, police radios, cell phones, what have you. As a rule of thumb, when a signal travels wirelessly, all control over level is lost. So, as a rule of thumb, any unit that receives a signal wirelessly has to have an AGC circuit.

If you've gone through the EM3 study guide, you know about negative feedback – taking some of a system's output waveform and sending it back to the input to correct waveform distortions. AGC is similar, but instead of feeding back a waveform, we're feeding back a DC control voltage whose amplitude depends on the output level. We use this voltage to adjust the gain of the preamp until we get the output we want.

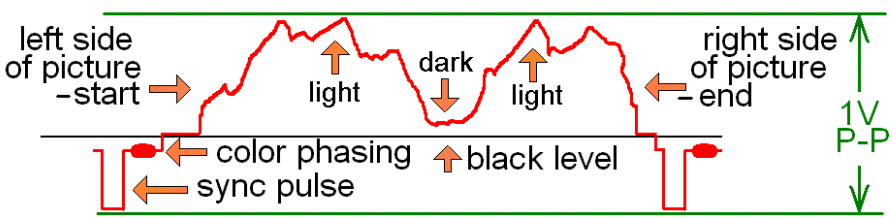


While we're at it, I should mention that a transmitting antenna has an impedance, and a receiving antenna has an impedance, but talking about the impedance of air is a little weird. (Air and space do have impedance characteristics,

but that's pretty esoteric and beyond the scope of this study guide.) So we think of the receiving antenna and receiver as a system, and the transmitter and transmitting antenna as a different system. As mentioned above, the impedance of a coax cable is usually 50Ω, unless we're dealing with video, in which case it's 75Ω. If the antenna is a different impedance, a balun is used to match it to the coax. FM still tends to use 300Ω balanced twinlead.

VIDEO LEVELS & IMPEDANCE

Baseband video, analog video as it comes out of the camera and travels around the studio, and also as it comes out of the yellow RCA jack of a DVD player, has a peak-to-peak voltage of around 1 volt.



baseband video -
one horizontal line

It is important that all the cables, amplifiers and controls in a system maintain this voltage – that is, that the system has unity gain throughout – because in baseband video, a change in voltage means a change in brightness.

Modulated video, video carried over the air by an RF signal, may have any voltage. Obviously, if you live a mile from the transmitter the voltage coming from your antenna will be much greater than if you live 30 miles from the transmitter. There's an AGC circuit in the TV to take care of that.

In cable TV systems, it is possible to exercise some control over levels because the system is hardwired and permanent. Long ago, a level of 1mV was established as the reference level in video distribution systems. The decibel equivalent is **0dBmV**, 0dB referenced to 1mV.

Actual signal levels in a properly designed cable system vary from a bit below 0dBmV to as high as +40dBmV (100mV). These are fairly loose limits and systems vary a lot.

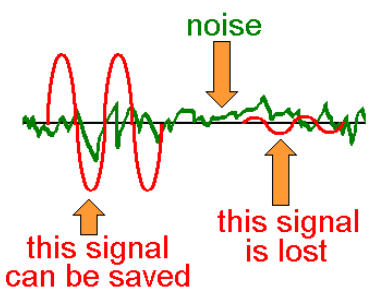
Whether baseband or modulated, the standard format for video interconnects is unbalanced coax cable, 75Ω impedance. Yeah, you knew that by now.

The exception is antennas. The output of a TV antenna is naturally balanced, and the standard impedance is 300Ω. In the old days, this was carried to screw terminals on the back of a TV set over flat 300Ω twinlead. Most TVs don't even have 300Ω inputs any more. Where an antenna is used, common practice nowadays is to install a 300:75Ω balun at the antenna and feed the signal down on coax.

AM & FM RADIO

The other place you'll still find 300Ω twinlead is FM antennas. There's a very simple kind of antenna called the "folded dipole" whose natural impedance is 300Ω, which is why twinlead and FM radio inputs and old TV inputs are 300Ω.

The only limits to the maximum level are how much power the antenna is transmitting, how close you can get to it, and how much signal it takes to overload the input to the receiver. There is a limit to the minimum level, however, which is dictated by the need to be stronger than the background noise that exists in every system, and in the environment. This is exactly the same reason a microphone signal sees a preamp before it sees a gain control.



What counts is having *enough* signal. There's almost no such thing as having too much signal, as the AGC can cut it down. In those rare cases where the signal is too strong – you guessed it, we put a pad between the antenna and the receiver.

AM radios usually require a millivolt or two of signal. They could be much more sensitive than that, but most AM radios are garbage. If you ever get to Minneapolis, drop in at the Museum of Broadcasting, which has some large, beautiful, expensive radios from the 1930s. Those were *real* radios. Most AM radios have permanently-connected internal antennas, and the Impedance is whatever the designer wanted it to be.

A very good FM receiver can put out reasonably noise-free monophonic audio when the signal level is about 1.3 microvolts or more (300Ω input). Stereo requires at least 10 microvolts.

DIGITAL LEVELS

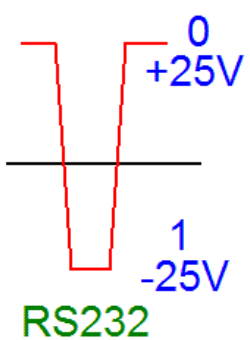
"Digital" means specific levels, like steps in a stairway. Inside equipment, that usually means two levels representing binary "1" and "0." For a long time, those two levels have been +5V and 0V, though voltages keep going down for good reasons explained in EM4.

Outside computers, things are different. For one thing, data often moves around inside computers in **parallel**, with all the bits in a Byte moving all at once over multiple wires. Outside a computer, data is usually **serial**, meaning the bits are sent as a series, one after another , on a single wire or pair of wires. Of course, there may still be multiple wires to permit several serial data streams to move at once.

Older systems use a single signal wire, referenced to ground. Newer systems use balanced pairs, which are more often called **differential pairs** in digital work; when one wire goes high, the other goes low. As in balanced wiring, this cancels incoming interference. It also greatly reduces outgoing signal radiation, since the average voltage on the pair does not change.

There are so many different ways to send data that I've just chosen a few of the more popular ones.

RS232 is one of the oldest standards. "0" is a positive voltage, up to +25V. "1" is a negative voltage, up to -25V. These extreme voltages were adopted because RS232 is not balanced or isolated from ground, so there's a real chance of picking up interference that will corrupt the data. This is a way to overcome noise by brute force. Also, RS232 is ancient, it goes all the way back to the clackety teletype days. Because of its high voltage, it could be received by completely mechanical (i.e. relays) equipment.



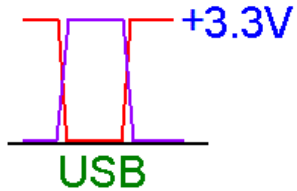
Nowadays, with digital equipment running on much lower voltages, many manufacturers just don't like the bother of generating + and -25V, which are not used anywhere else in the system. RS232 is often as low as + and -9V, and can be as low as + and -5V. If you're working with an RS232 system that's giving trouble, check the level. Boosters are available. Sometimes sticking a booster in the line, like an "unpad" or "anti-pad," is all it takes to fix the problem. The best place to put it is near the transmit end.

I've seen a few boosters that present a sort of "pseudo-balanced" input, which goes a long way toward correcting ground-related problems. These should go near the receive end.

Transmit and receive impedance is fairly high, 3kΩ to 7kΩ. At the frequencies involved, cable impedance is irrelevant. A greater problem is cable capacitance, which (due to the high impedance) sharply limits the data rate with long cables.

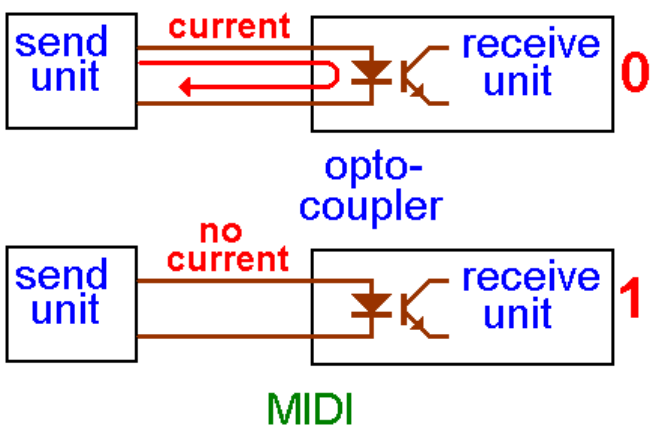
There is no particular connector specified for RS232.

USB uses a differential pair whose two wires switch between +3.3V and 0V, as shown in the illustration to the right as red and purple traces. A USB connector also has a pin with +5VDC on it to do things like supply power to a hub or charge a cell phone.



The standard USB impedance is a differential 90Ω. USB doesn't bother to address ground problems because USB cannot work over long distances, so ground-differential problems don't often develop.

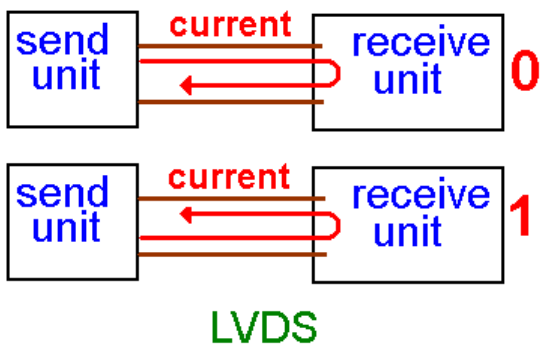
MIDI uses a 2-wire current loop. Of course, there's a voltage across the wires, but that's to drive a current, and information is transmitted as current changes. "1" is the no-current state. "0" is the state when current flows. Since it's a current loop, impedance considerations don't mean much. The specified current level is 5mA.



MIDI is the one system that has no ground loop problems. At the receiving end, the cable terminates in an optical coupler, which isolates the grounds. MIDI has a standardized bit rate of 31.25kHz.

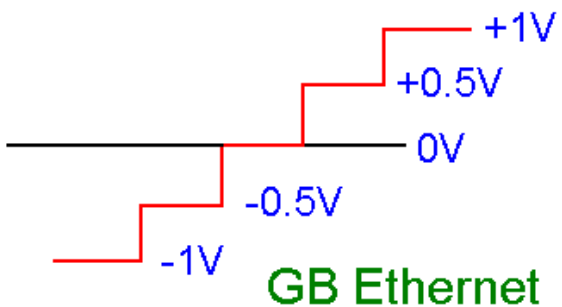
The reason MIDI treats grounds so carefully is because, though it's carrying digital signals, its intended use is to provide control to multiple audio devices, and its designers didn't want it to create ground loops.

LVDS, short for **low voltage differential signaling**. Despite its name, it's a current-loop system. It's different from MIDI in several ways: 1) frequency is not tied to 31.25kHz 2) there is no optocoupler 3) loop current is 3.5mA 4) current flows for both 1 and 0. LVDS indicates a state change by reversing the current.



LVDS does not specifically deal with grounding problems, but current loops are less sensitive to ground problems than voltage signals.

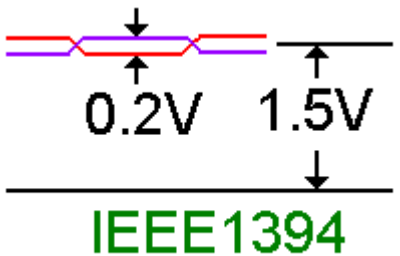
ETHERNET uses a differential 100Ω pair and the voltages depend on speed. In older systems, the voltages are +2.5 and -2.5V. Gigabit Ethernet uses five voltage levels: +1V, +0.5V, 0V, -0.5V, -1V.



If binary (2-level) operation is so great, as described in EM4, why would gigabit Ethernet use five? Well, we all want faster data transmission. There is a limit to the bit rate any interconnect can carry, but if each bit can carry more than one binary bit of information, that's a way to get faster speed. Two binary bits can encode 4 levels of information. Two 5-level bits can encode 25 levels of information, more than six times as much.

Fast data systems like GB Ethernet have a potent weapon against ground problems. Since their signals are very high frequency, they can simply insert a high-pass filter in the signal chain and block energy at low frequencies, which is where ground problems usually occur.

FIREWIRE / IEEE1394 uses a balanced pair. Both wires typically have around 1.5VDC on them, and the difference across them often amounts to only 0.2V.

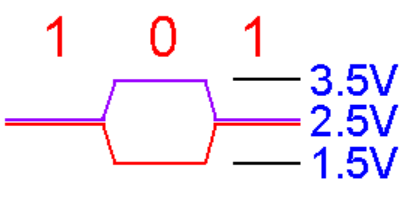


The voltages are not well defined, which would be pointless anyway, because Firewire is intended for very high speed data, and at those data rates, attenuation between one end of the cable and the other is severe. It's a bit like the wireless problem: the signal level can be anything from 0.2V peak to peak, down to millivolts.

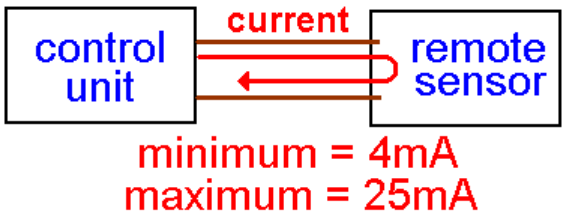
So, in high-speed data systems like Firewire, the receiving unit “learns” the characteristics of the specific cable it's connected to, and applies corrective technology. That's AGC by another name, though in a cable system, the gain doesn't vary so much that the AGC has to be continually adjusted as in a wireless system.

THUNDERBOLT (data) / **DISPLAYPORT** (video) uses similar techniques, but there are four separate data pairs called lanes. There's also a DC pin that puts out 3.3V at 0.5A. That's not enough to power much, but it's just intended for control functions. The developers assumed whatever it's plugged into will have its own power supply.

The **CAN BUS** or **controller area network bus** was developed for cars and is now widely used in industry. On the differential data lines, the inactive state is logic “1,” where both wires sit at about 2.5V. When a logic “0” occurs, one wire is pulled down to about 1.5V and the other pulled up to about 3.5V. It's a 4-wire bus; the other two wires are +12VDC and ground. There is no specified connector.



Industrial control applications often use a **4-25mA current loop**. The lowest current, usually corresponding to a measurement of zero, is 4mA. The highest current is 25mA.



This is a pretty clever setup. Having some current flowing all the time means a sensor connected into the loop can be powered by the loop itself, rather than requiring a separate power source. This avoids a lot of ground loop problems. Also, if the current ever goes to zero, the system knows the line has been broken. And using a current loop means cable capacitance doesn't matter much.

WIRELESS DATA TRANSMISSION

The thing that's different about wireless digital signals (compared to analog signals) is that, much of the time, by the time they get to the receiver, they're extremely weak. In many cases, like Bluetooth, they start out weak and only go a few feet. Applications are beginning to show up where maximum distance is an inch. Essentially, the units are plugged together, except without plugs.

With wireless, we're working with so many different levels that I'm not going to talk about specifics. But since wireless signals are so often weak, I want to talk a bit more about something I mentioned above.

NOISE

I've mentioned the small amount of electrical noise in any system which sets a limit to how weak the signal can get and still be recovered. Many wireless systems routinely work with signal levels that are not far above this **noise floor**. Noise is everywhere, not just in RF and wireless systems but in every electrical system. So I will throw this out here and you can memorize it if you choose.

The minimum, can't-get-lower noise depends on impedance, frequency range and temperature. Specifically:

- Noise is proportional to the **square root** of impedance. Go from 50Ω to 200Ω, multiplying impedance by 4X, and noise is multiplied by 2X.
- Noise is proportional to the **square root** of frequency range. Change a 1kHz-to-2kHz frequency range to 1kHz-to-8kHz, multiplying range by 4X, and noise is multiplied by 2X.
- "Natural" noise, called **white noise**, has equal energy in every equal frequency span, e.g. as much noise between 1kHz and 2kHz as between 2kHz and 3kHz. However, we often look at frequencies proportionally; that is, we'd compare the range between 1kHz and 2kHz to the range between 2kHz and 4kHz. Those spans are the same, proportionally, but different by absolute measurement. This means that, in many systems, noise is concentrated at higher frequencies.
- Most people do not calculate noise levels. Instead, they memorize a reference level and scale from there. A convenient reference, especially for people doing RF work, is an impedance of 50Ω, a frequency span of one Hz, and room temperature (around 25° C). Under those conditions, noise is about one nanovolt, 1nV, 10^{-9}V. Suppose we want to find the noise in the frequency band between 20kHz and 30kHz. That's a 10kHz span, 10^4Hz. Noise is proportional to the square root of bandwidth. The square root of 10^4 is 10^2. So, going from a 1Hz span to a 10kHz span, we get 10^2 times as much noise, or 100nV in a 50Ω system. Impedance scaling works the same way. If the impedance is not 50Ω, we scale according to the square root.

The lowest acceptable signal level is determined by how much higher than the noise floor it has to be. In high quality audio, even quiet sounds must be 60dB above the noise floor. In many RF systems, a 3dB margin is adequate. This is called the **signal-to-noise ratio** or **SNR**.

End of Chapter 8

EM5 chapter 8
INTERFACING ELECTRONIC PRODUCTS: CABLES AND CONNECTORS

Objectives of this chapter:

- *discuss whether it is wiser to make or buy a cable in various circumstances*
- *describe factors to take into account when choosing cable*
- *describe / demonstrate how to prepare wire and cable ends for various connectors*
- *describe / demonstrate wire tinning*
- *define and discuss "drain wire"*
- *define and discuss "drip loop"*
- *describe / demonstrate how to attach cables to various connectors*
- *describe / demonstrate proper lug crimping*
- *describe / demonstrate how to make a Western Union spice and various crimp splices*
- *explain where a shield is usually grounded and why*

In this chapter you're going to learn how to make the more common types of cable.

It's worth asking, "Should I make cables?" and even, "Can I make cables?" There's a lot to be said for buying pre-made cables. They're usually tested by the manufacturer and you can depend on them to work. The labor cost of making a cable might be greater than the extra cost of buying one. And the more complicated cables, with smaller connectors (e.g. Thunderbolt) are difficult to get right by a field tech. Also, pre-made cables where the connectors are molded on are more resistant to flexing and yanking damage.

cable molded onto connector

However, you will run into cases where it's not practical to use pre-made cables. For one thing, you may be pulling them through holes that are too small for the connectors. A tech should learn how to prepare the ends of the wire and install the more common connectors; it's knowledge you're bound to need.

You'll find that some tools work better for you than others, and they may not be the same tools the next tech prefers. To each their own. If your school has a variety of tools, or you work in a shop where different people use different tools, try out several kinds to see which you like best.

CHOOSING THE RIGHT WIRE OR CABLE

I can't possibly list every application, and we've already talked a lot about wire and cable in chapter 2, so I'll just summarize some of the considerations:

- type of signal, including frequency
- need for shielding – or not
- balanced – or not
- current and voltage requirements
- characteristic impedance, where that applies
- signal loss per foot at the frequency you're dealing with
- physical size
- physical characteristics like fire rating

In most branches of electronics, everybody uses one or two standard kinds of cable, and all the tech has to know is which one to use and when something other than a standard cable is called for.

WIRE PREPARATION

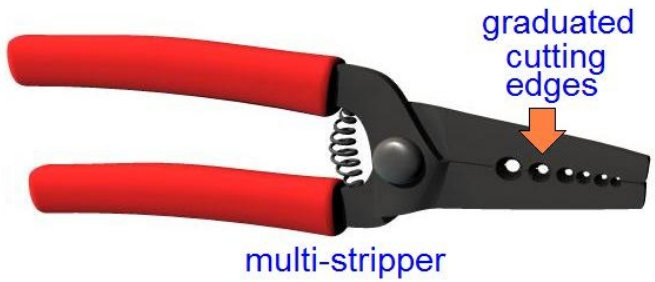
Most wire is insulated, which means we have to strip a short length at each end to make connections. There are right and wrong ways to do this, and a lot depends on what connectors the wire will be attached to.

STRIPPING PLASTIC & RUBBER-JACKETED WIRE

The first thing you'll have to do is remove a short length of the rubber or plastic jacket to expose the end of the wire using a **stripper**. No, not that kind of stripper. The kind meant for stripping insulation from a wire. Behave yourself, this is a family show.

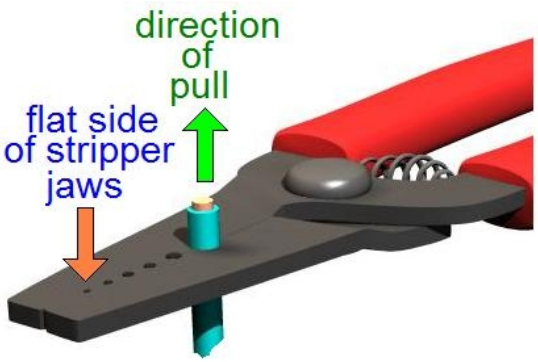
The trick is to cut through the insulation without nicking the wire. If you nick a solid wire, it will be weaker at that point and flexing will break it after a while. If you nick a stranded wire you'll cut off a few strands, which may not be too serious (although you *must* collect and dispose of the broken ends – don't let them fall into the equipment!) but that's hardly the mark of an expert tech.

Not nicking the wire is largely a matter of setting the stripping tool for the wire size you're using. A stripping tool has a hard stop that keeps the jaws from clamping down on the wire. One common type is the long-jawed stripper with half-moon cutting edges of various sizes.



The other most-common type has a single pair of V-shaped cutting edges and an adjustable limit (often called a **Miller stripper**.) You should try both types. I use both types.

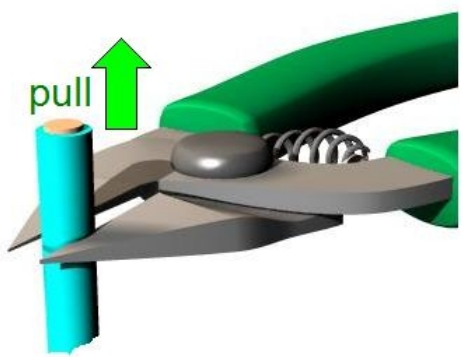
With some strippers, orientation is important. The flat part of the cutting edge should be toward the end of the wire. Put the wire in the right slot, clamp down, and pull the insulation off the end.



With a Miller stripper, both jaws are the same, so it doesn't matter which way you hold the tool. One drawback of the Miller stripper is that the V-shaped cutting edges don't cut the insulation all the way around. If you're having trouble removing the insulation, clamp down, loosen a little, rotate the tool or the wire 45 degrees, and clamp down again.

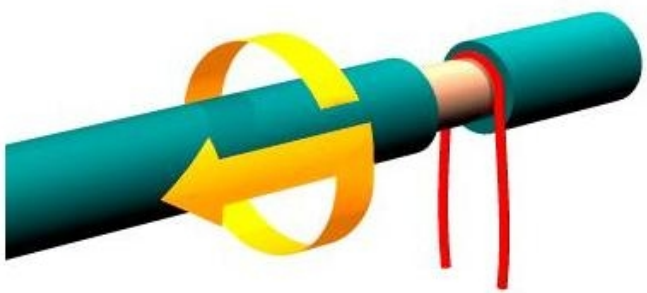
An **automatic stripper** holds the wire, cuts through the insulation and pulls it off in one motion. I find it too large and clumsy, but if you do a lot of wire stripping you might like it. Don't bother with the cheap ones, they just make a mess of the wire. Get a professional model or stick with the non-automatic strippers.

Suppose you need to strip a wire but you find yourself without a stripper. In theory, this should never happen. In real life, it happens to everybody. In a pinch, you can strip a wire with a pair of side cutters. The cutters must be held as shown, with the flat side toward the end of the wire as with the long-nose stripper. Since you have no automatic limit, you must be very careful how hard you clamp down on the cutter. Clamp and rotate the wire a bit, several times, to cut the insulation all the way around.



This takes practice, which you might as well do ahead of time so you'll be able to use this technique when you need it.

In some critical applications where there will be a lot of vibration and a broken wire could spell disaster – the aerospace industry, for example – **hot wire** stripping is used. Current is passed through a wire loop to make it hot enough to melt the insulation on the wire being stripped. The wire is rotated, then pulled back, leaving a bare end. This avoids any chance the wire will be nicked.



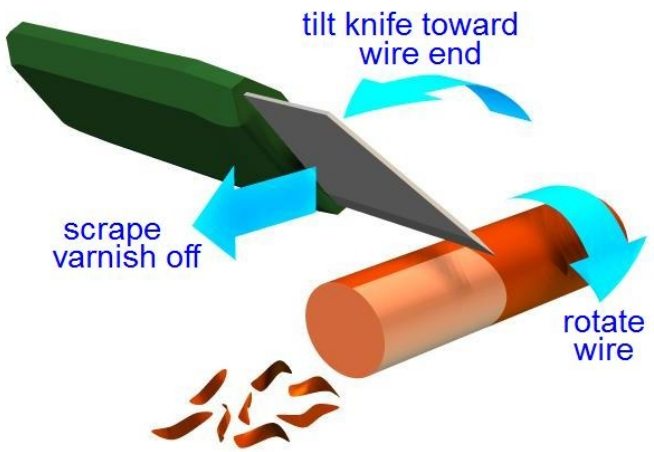
Speaking of vibration, I've mentioned this before but it bears repeating. With power-line (e.g. 120VAC) circuits where there will be vibration, such as power to a motor, the Electrical Code requires stranded wire with a rubber jacket.

STRIPPING VARNISH-INSULATED WIRE

As mentioned in chapter 2, “varnish” is a generic name for any kind of insulation that's painted onto a wire. Most “varnishes” are plastic these days. Most cables don't contain varnished wire, but it's worth knowing how to strip the stuff in case you do run across it.

There are three ways to get the insulation off:

- scraping
- melting
- dissolving



To scrape the insulation off, use a knife or box cutter. The blade must be tilted toward the end of the wire, otherwise it will dig in and gouge the conductor.

With a sharp blade, you shouldn't have to press hard enough to damage the wire. Once you have scraped some insulation off, rotate the wire a little and scrape off another piece. Keep rotating and scraping until the whole end is exposed. This is another one of those things that takes practice. Once you've done it a few times, it should take less than 20 seconds per wire.

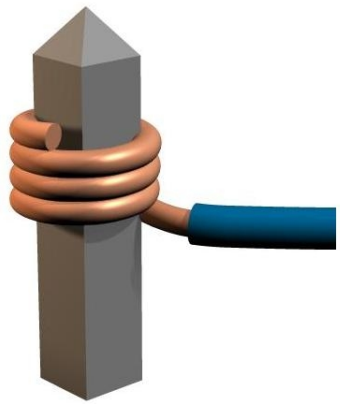
An alternate method is to use a small file or sandpaper. The advantage is that you're less likely to nick the wire. The disadvantage is that it gouges up the wire along its length. This method works better on large-diameter wires than small ones.

Varnish can be melted off, but it takes a *very* hot iron, and you're left with a blackened mess that has to be cleaned up with solvent. The varnish should be removed and cleaned before the wire is attached to a terminal. For smaller-diameter wire, melt a blob of solder on the iron and push the end of the wire into it. Starting with the end of the wire in the solder blob heats up the wire and encourages the insulation to melt.

Sometimes you have no choice but to attach the wire first and then melt the varnish. This results in a bigger mess and you have to be careful not to apply heat to the terminal so long you ruin the part.

There are only a few chemicals that will dissolve modern plastic varnishes. You will only wind up using them if you work with varnished wire a lot, and your employer has set up the workplace to use them. After the varnish is removed, the chemical must be thoroughly cleaned.

HOW MUCH TO STRIP



There is no hard-and-fast rule, but the proper length is usually whatever will leave just a little bare wire when the connection is finished. The jacket should not touch the connection, especially if it's a solder joint, but it should not be so far from the connection that a lot of bare wire is hanging out. It certainly should not leave so much bare wire that adjacent wires could short together. As a rule of thumb, 1/8" on small connections and ¼" on large ones is appropriate.

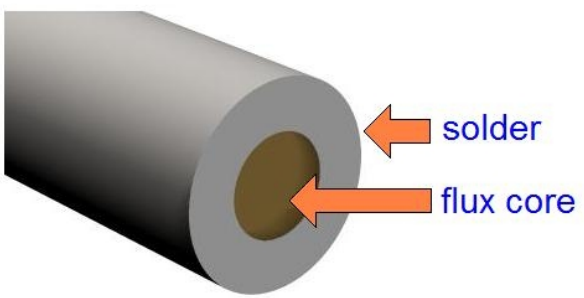
By the way, the connection method shown above is called **wire wrap**, popular in older equipment and still used occasionally. The wire is pulled hard around a square terminal. If you look closely, you'll see that the corners bite into the wire, four times per turn. This can be more reliable than a soldered connection.

TINNING THE WIRE

When the end of the wire is going to be soldered onto something, it may be wise to coat the wire with tin or solder. Hookup wire even comes pre-tinned. This makes soldering easier.

When copper wire is exposed to air, it develops an oxide film. This must be removed so the solder has access to the bare copper. The film is dissolved by a chemical **flux**, which is a paste or liquid applied to the copper. It must be applied as the connection is being made, because the oxide film forms almost immediately upon contact with air.

There are two kinds of flux: **acid flux**, which must ***never ever*** be used with electronic equipment, and **rosin flux** or a chemical that mimics it. Solder meant for electronic use usually has a hollow **core** with rosin flux in it, so application of flux at the right time is automatic.



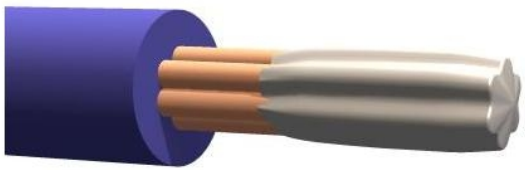
One way of tinning the wire is to simply apply an iron to it, melt some solder, and spread it around. You must hold three things: the iron, the wire, and the solder. Last time I checked, most techs have two hands, so you'll have to get good at holding the wire and the solder with one hand. If they ever figure out how to teach orangutans to solder, a lot of us are going to be out of work.

Alternately, you can brush some liquid or paste flux on the wire, put a blob of solder on the iron, and run the wire through it.

A word of warning about liquid flux: if you tip the bottle over, it makes a huge, sticky mess that requires solvent to clean up. I've had that accident so many times that I finally took a block of wood and drilled a hole in it to hold the bottle.

Tinned wire also develops an oxide film, but it takes months. Whether you tin or not, the wire and whatever it's being soldered to must be clean and shiny. A pencil eraser works well to remove a modest amount of tarnish.

If you're working with stranded wire, tinning keeps the strands from getting messed up. Don't apply too much solder; you should still be able to see the outline of the strands.



If the stranded wire is going to be put under a screw head or other device that exerts pressure, it should *not* be tinned. Twist the strands together to keep them neat.

There is disagreement about how far to tin the end – so it just touches the jacket, soaks under the jacket, or stops a little distance from the jacket, as shown above. Most techs feel the last option is best.

PREPARING SHIELDED CABLE

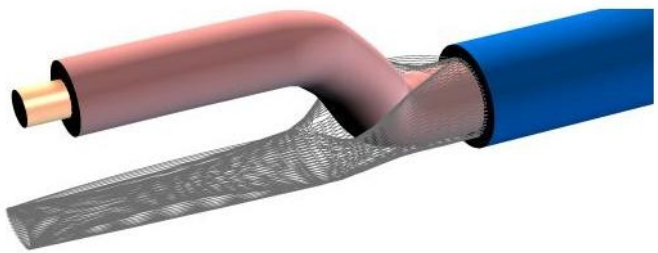
When you're working with shielded cable, you're dealing separately with the inner conductors and the outer shield.

How you proceed depends on the type of cable. As a general rule, don't strip more of the insulation than you need to. It just makes things harder and raises the possibility that wires will short together if the cable is twisted or flexed. Also, the longer the unshielded length of signal wire, the more interference radiated or received.

Braided Shield

If the signal wire and the shield are going to two different places, as in most audio connectors, strip enough of the outer jacket to un-braid the shield and pull the strands to one side. If the connector can't capture all the strands, tin them. You cannot afford to have flyaway strands that may short the signal. Stripping ¾" from the outer jacket and ¼" from the inner conductor is usually about right, unless you're working with a small connector that requires shorter wire ends.

If you need a comparatively long length of inner wire exposed, say 2 inches, don't try to unthread that much braid. Take an awl and push the strands aside until there is a hole in the braid that you can pull the inner wire through.

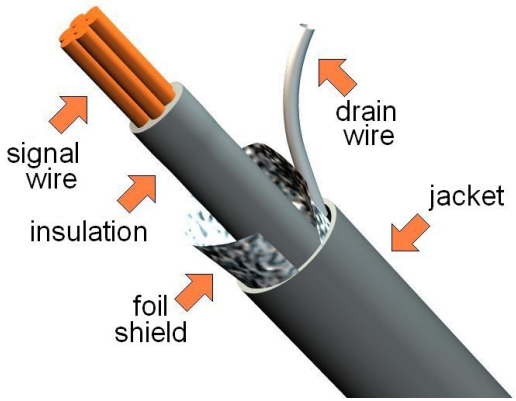


If you're dealing with rubber-jacketed cable, there will likely be cloth or string inside the cable. These are to add strength, and in cables with more than one wire inside, to fill out the cable so it can be round. Trim these off with a sharp side cutter.

An RF signal require a completely shielded path that is as smooth as possible, so an RF connector does not involve un-braiding the shield. I will show you how to handle the shield when I talk about each type of connector.

Foil Shield

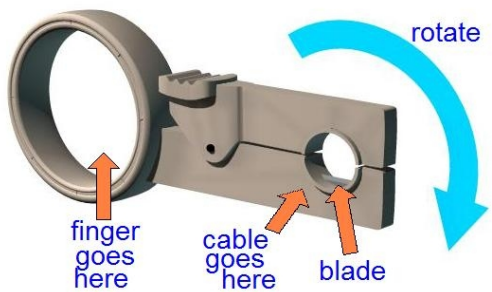
In many applications, an aluminum foil works as well as a braid, sometimes better. The shield cannot be soldered and



it's delicate, so instead of expecting you to connect to it, the cable manufacturer either makes it to work with a crimp-type connector, or includes a tinned **drain wire** that's in contact with the foil all along its length. You just trim back the foil and then connect to the drain wire.

CABLE STRIPPING TOOL

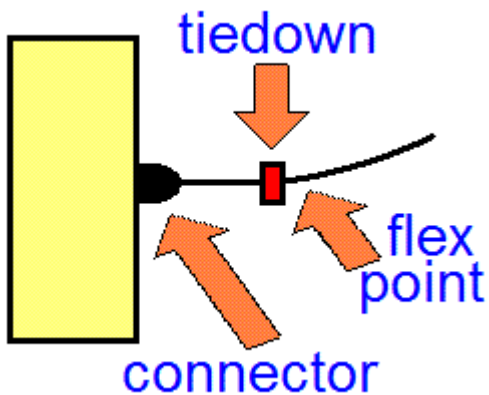
There's a cool tool available for stripping the outer jacket of a coax cable, and it's cheap. You put the cable between jaws in the tool and clamp down, then spin. A sharp blade is precisely positioned inside the hole. It cuts just deep enough to go through the jacket but doesn't nick the conductors.



Simple ones go for as little as $3 on Ebay. If you work with coax a lot, it's the only way to go.

CABLE SUPPORT AND STRAIN RELIEF

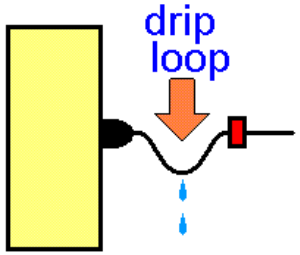
Flexing or jerking on a cable anywhere along its length is undesirable, but flexing or jerking it at or near a connection point is much worse; the connection is guaranteed to break eventually. A tech should be willing to install wire supports and tiedowns as necessary. The general aim is to move the flexing area down the wire, away from the connector, and spread it out so the wire doesn't flex sharply at any point.



Keep in mind that at the highest frequencies, putting a sharp bend in a cable changes its transmission characteristics.

If the cable is to be installed outdoors, be sure you don't set it up so rainwater runs down the cable and into the connector. This will quickly ruin the connection, and water may get into the unit and ruin it too.

Instead, make a **drip loop** that drains water away from the connection. It's a small detail but it can prevent big problems.



CONNECTORS

There are several reasons to use the proper connectors:

- you want to be able to plug equipment together
- you do *not* want to plug the wrong kinds of equipment together
- there are well-established standards for each type of signal, in some cases mandated by law
- at high frequencies, the connector affects performance

Most connectors include some kind of built-in strain relief, which varies from good to almost useless. In many cases it's questionable whether the strain relief is worth using. If you can tie down the cable near the connector, so any flexing is kept away from it, that's a good thing to do.

At the risk of insulting your intelligence, I'll remind you that connections must be securely made, that wire placement must be such that things cannot accidentally short, even if the cable is twisted or jerked on, and all flyaway strands

must be trimmed off – but you're going to practice until you don't have flyaway strands, right?

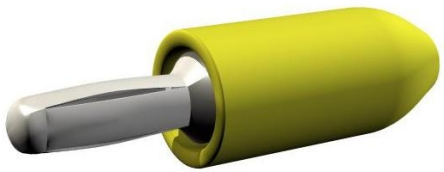
The signal connections in most connectors are small pins that mate with small sockets. These are called “male” and “female” respectively, for obvious reasons.

I've heard that the founder of Switchcraft was a conservative type who was uncomfortable with the sexual connotations. According to the story, he insisted on calling male connectors **plugs** and female connectors **jacks**. Since churches are major users of electronic equipment, it's likely that many of my readers are similarly conservative, and out of respect for them I'm going to observe the Switchcraft tradition.

Some connectors are soldered on; in other cases, the connections are crimped. Each type of crimp connector has a crimping tool made just for it. There is no such thing as a universal crimping tool that works with every kind of connector.

No matter how much you read this study guide, you won't really get it until you have actually worked with the connectors. So, just as a suggestion – a very STRONG suggestion – you should have these connectors and tools in your hands as you read about them, and go through the actual process.

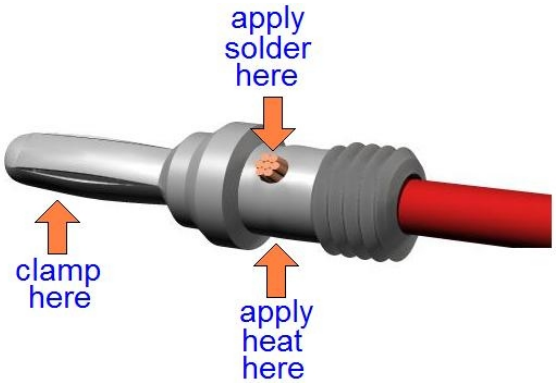
BANANA PLUGS



You can't get much simpler than a banana plug, which is just a blunt 4mm-wide finger. The sides of the finger bulge outward and are spring-loaded, so as to make reliable connection with the jack, which is a stiff tube.

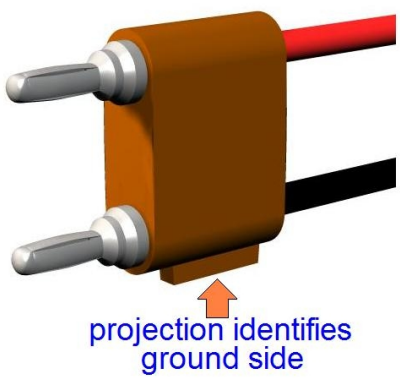
The kind I like best has a hole in the back to insert the wire, and a hole in the side for applying solder. Clamp the tip in a vise (gently, so you don't flatten it). Slip the shell over the wire, then strip maybe $^{1}/_{8}$” of wire. Stick the stripped wire in the back of the banana and push. The plug will bend the wire up through the hole in the side. (You may want to pre-bend it a little.) Apply a soldering iron to the body, and apply solder to the wire end. Then when it's cool, screw the shell on.

About the third time you do this, you'll forget to put the shell on first. That's called learning the hard way. Could be worse. TV cameras used to have maybe fifty connections, and more than one tech has had to redo all fifty after forgetting the shell.



If the wire and jacket are small enough, I like to stick the jacket right up inside the plug as shown above. Banana plugs have zero strain relief, and flexing will eventually break the wire. Running the jacket up into the plug reduces bending at the connection a little.

When you need both signal and ground connections, you can use **dual banana plugs**. The standard spacing is ¾" apart. A bump on the side of the plug identifies the ground side, though of course you can flip the plug over if you want – which may be a good thing or a bad thing depending on the application.



In some European countries, AC outlets have two holes that are spaced close enough to ¾" that you can put a dual banana plug into them. This is obviously dangerous, and for this reason you can't buy dual banana plugs in Europe.

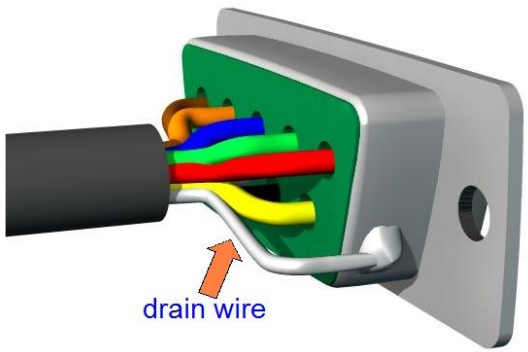
Banana jacks are a lot simpler, because most of them are chassis mounted. Drill a hole, insert the jack from one side, screw on the nut from the other side and make connection to the terminal sticking out the back. It's so obvious I'm not even going to make a picture.

D CONNECTOR

Though the use of D connectors for computer monitors is shrinking, there are still plenty of other places they're used.

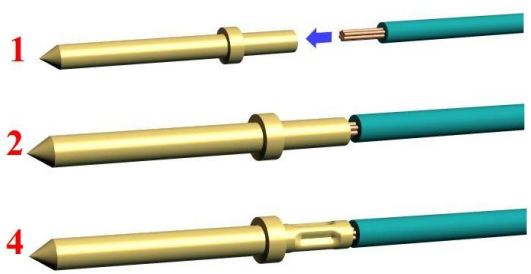
In the solder version, each pin has a solder cup at the back. 50-pin D connectors, and 15-pin miniature D connectors, have 3 rows of pins. Be sure you connect the middle row before the last row, or you won't be able to get at those pins.

Depending on the cable, a shield or a ground wire may need to be soldered directly to the shell. The best location is on the end as shown below. Anywhere else, and the solder bump will prevent you from putting the shell on.



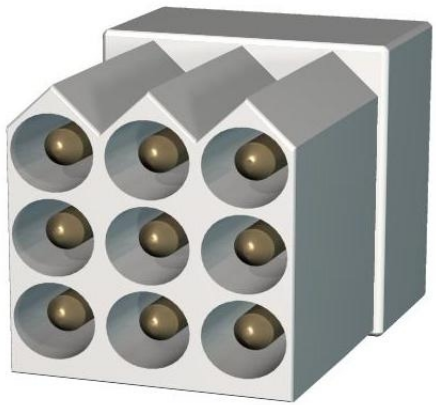
The illustration above shows a kind of D connector where the pins are crimped onto the wire, then inserted into the connector body. The crimping tool is made specially for these pins. The steps are:

1. Strip a short length of wire.
2. Insert into pin.
3. Insert pin and wire into crimper – follow manufacturer's directions.
4. Squeeze crimper handles.
5. Remove pin from crimper.



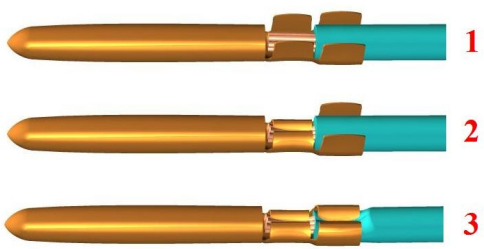
6. Inert into back of connector. Push in until you hear a click; that tells you the pin is locked in place.

MOLEX CONNECTORS

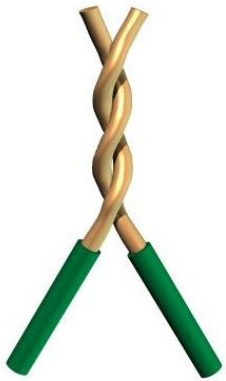


First made by Molex, now made by lots of people, widely used in high current applications.

Almost all Molex-style connectors use crimped pins. Each pin is crimped twice. The front part is crimped over the bare conductor, the back part is crimped over the jacket. You have to strip off exactly the right amount of jacket, which you can figure out by holding the wire up next to the pin. You also have to use the right crimp tool. The illustration shows a properly stripped wire ready for crimping (1), after the first crimp (2) and after the second crimp (3).

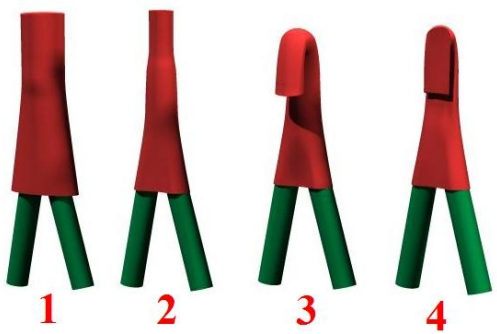


After a pin is crimped on, you insert it into the back of the connector and push until it clicks, like a D connector.



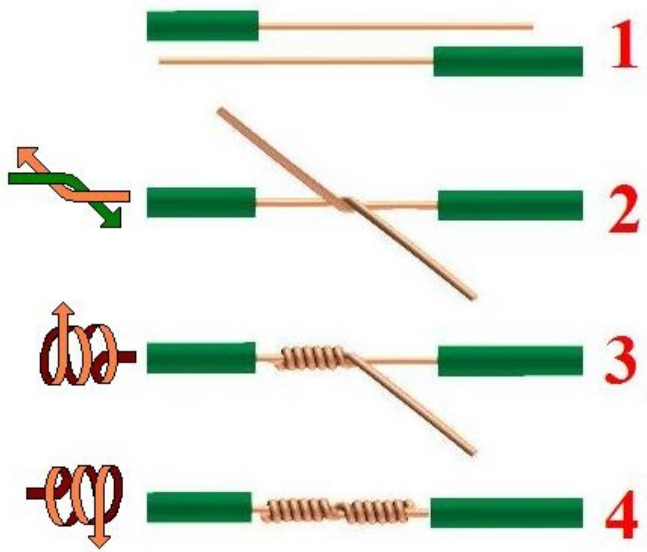
SPLICING WIRES

Now and then you'll need to join wires together. The simplest way is just to twist them as shown to the left. It's quick, dirty, and there's nothing wrong with it as long as nobody is going to pull on the wires, but don't expect it to be reliable unless you solder it. It doesn't matter whether the copper is tinned or not; both copper and tin oxidize and the connection will fail if you don't solder it.



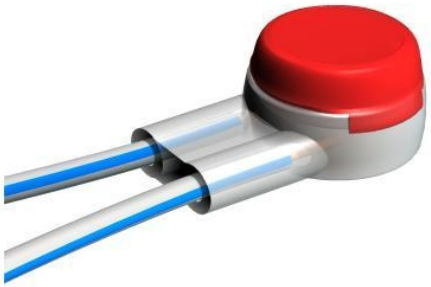
If you want to put shrink tubing on the joint to protect it, here's the method I use. (1) Cut a piece of tubing and put it on, leaving ½" of tubing beyond the end of the joint. (2) Shrink it down. (3) While it's still hot and flexible, fold the top over. (4) Take a large pliers and flatten the tubing. The pliers will quickly wick the heat away, solidifying the tubing and leaving a neat cap that will stay in place.

Dozens of types of wire-to-wire splices have been developed. The best, probably, is the **Western Union splice**, which is especially good if the wire's going to be pulled on. You strip quite a bit of insulation off the wire ends and then follow the four steps shown here. Solder when you're done. If you're going to put heat-shrink over the



splice, remember to slip the tubing over one of the wires before you start.

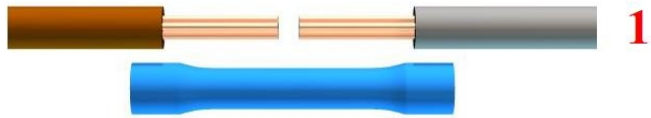
For telephone field techs, soldering is often out of the question. They need a way of making quick, reliable splices. It also has to be cheap, cuz they make a lot of them. There are various kinds of crimping connectors available like the one to the right.



Or you can twist on a **wire nut**, which just screws onto the wires. There are many kinds, and many are garbage. Some are just plastic, but I wouldn't use one that didn't have a threaded metal insert. The ones I like best have a cone-shaped coil spring inside.

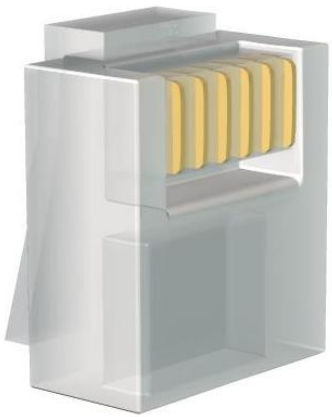
An alternative to the wire nut is the **crimp cap** shown to the right – slip it on and pinch the center. Crimp caps work better with stranded wire than solid.

Another crimp connector is the **butt joiner**. These work best with fairly large (e.g. no. 14) stranded wire, not so well with small wire and solid wire. You strip the wire ends as in (1) below and then insert and crimp twice, one for each wire end, as in (2). I'm going to discuss crimping in a lot more detail when we get to crimp lugs a little later on.



None of these joints are waterproof. You can get **internal melt** shrink tubing that's coated with glue on the inside. When you apply heat, the glue gets gooey and the tubing shrinks, squeezing the glue into the connection. Supposedly this makes a waterproof connection. I don't trust it. The real benefit of the glue is that it forms a firm, can't-pull-it-off bond with the joint. The only reliable way to deal with water is to use special waterproof connectors, or to lay out the cabling so the splices are where the water ain't.

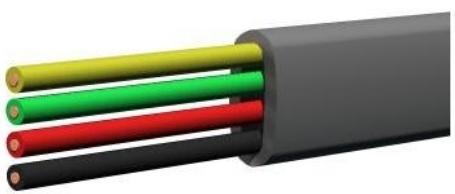
MODULAR / RJ CONNECTORS



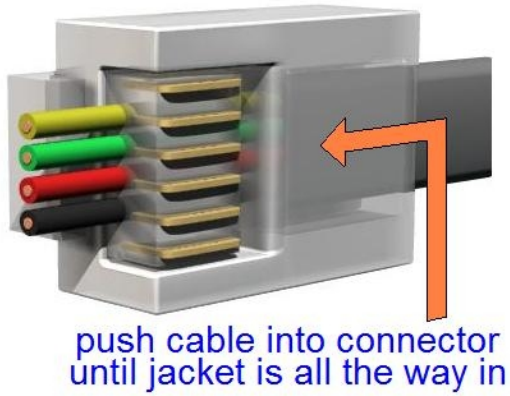
For use with CAT5 / CAT6 unshielded twisted pair (**UTP**) solid wires, and also with flat telephone cable. The type used with telephones is called a **6P4C** connector; 6 positions, 4 conductors. The outer two positions are not used.

There are two types of connector: ones that don't have holes in the end for the wires to stick through, and ones that do. I can't imagine why anyone would use the former type, as they require the jacket to be stripped to precisely the correct length. With the push-through type, you only have to be sure you've stripped off *enough* jacket. The crimping tool cuts off the excess wire lengths at the same time it crimps the connector.

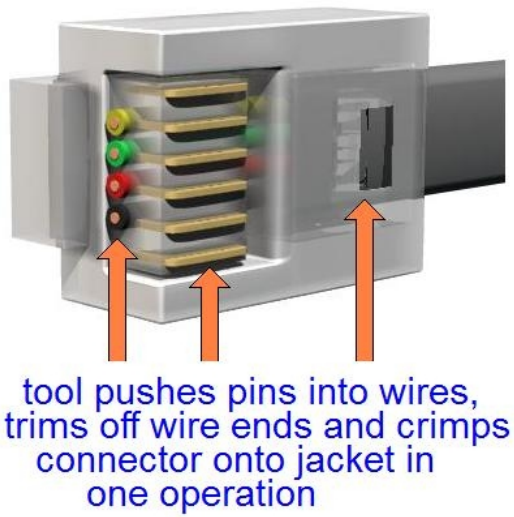
- Strip off ½" to ¾" of outer jacket. It is not necessary to strip the individual wires.
- If you're using flat telephone cable, the four wires will be sticking out in their proper order. If you're using UTP, untwist the wires and straighten for insertion.



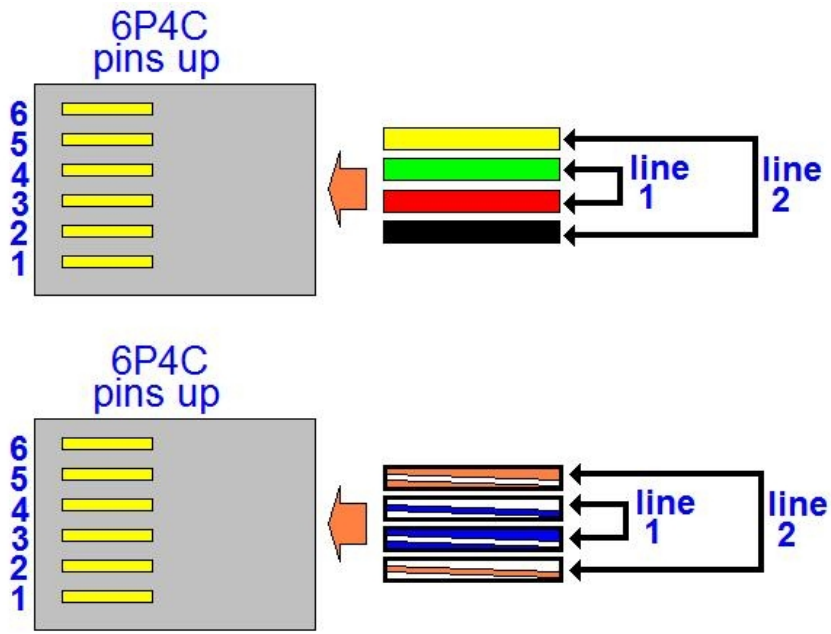
- Insert into connector.



- Crimp.



Note that, when used for telephone lines, the two wires in the center (red & green) are the first telephone line and the outer wires (black & yellow) are the second line. This way, a single-line phone can be plugged into a 2-line jack, and a 2-line phone can be plugged into a single-line jack (although only one line will work). Pins 1 and 6 are not used.



With UTP pairs, pins 2-6 are:

2. White, orange stripe
3. Blue, white stripe
4. White, blue stripe
5. Orange, white stripe

The 6P4C connector is also called an **RJ11** connector, which is not really the same thing. "RJ" is a *wiring* standard for a single phone line (2 conductors). When wired for 2 lines, it becomes RJ14. But the RJ11 designation is so widely used that a tech is more likely to understand what you're talking about if you say RJ11 than if you say 6P4C.

CRIMP LUGS

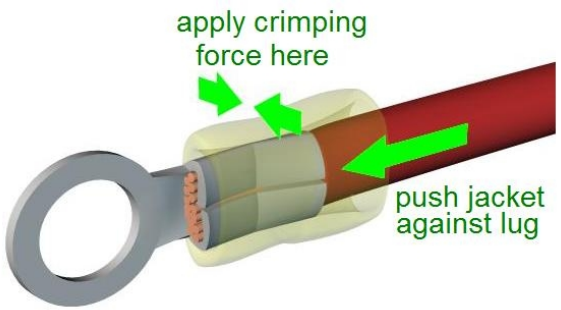
Crimp lugs come in many forms: spade-shaped, tabs, eyes and so on, in all quality ranges from junk to military spec. What you choose to work with, both in terms of the lugs and the tools, depends on how reliable you need the connection to be. Given that the finest lugs are around 20 cents, it doesn't make much sense to use poor ones.

The color of a lug's plastic sleeve tells you what wire size it's designed for.

- Red – 22ga. to 16ga.
- Blue – 16ga. or 14ga.
- Yellow – 12ga or 10ga.

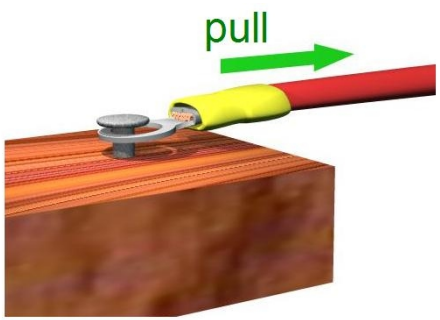
Larger lugs, e.g. for welders, usually don't have plastic sleeves. You can put on shrink tubing if you like.

Crimp lugs can be used with solid wire, but they're most reliable when used with stranded wire. The stripped end is inserted in the back of the lug until the insulation butts up against the metal tube part of the lug, inside the plastic sleeve. If the wire is stripped to the correct length, the strands will be just visible from the eye end. The crimping tool is then placed over the middle of the metal tube and the tube is squeezed onto the wire. Do not tin the wire. But if the strands are factory-tinned, that's okay.

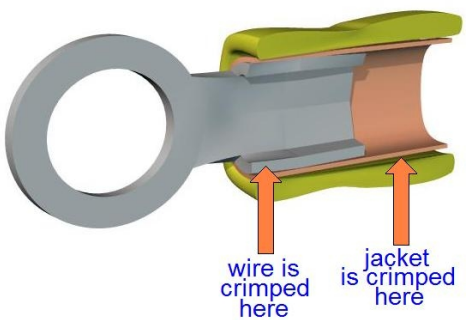


The most important consideration is to be sure enough pressure is used to create a **cold weld** between the wire and the lug. I'm not sure it's possible to do this with a cheap hardware store crimper. A professional crimper will have a ratchet mechanism that does not permit you to relax the tool until the crimp is complete. The best crimpers are hydraulic or electrically operated, and they cost a bundle. That kind of investment may not be worthwhile for you, especially if you're not working with high voltages or any situation where a failed crimp can be dangerous. But I've seen a lot of "professionally" done crimps where the wire just falls out of the lug. There's no excuse for that.

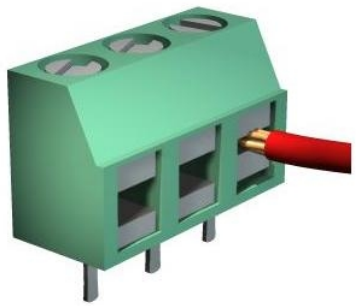
You should practice; you never know where your career will take you. Take an eye lug and a wire and crimp them together. Then nail the lug to something. Take a fish scale and pull on the wire. A proper crimp should take at least 20 pounds of pull to come loose. (Military equipment requires 38 pounds.) If the wire breaks before the crimp does, you know you've done it right.



Most of the lugs you see in hardware stores are lower quality than what a professional would use. Better lugs have a second metal tube around the first. You crimp twice: at the front of the tube, to crimp the wire, and at the back of the tube, to clamp the insulation. The illustration to the right shows a cutaway section.



The best lugs have a funnel shape inside to guide the strands, so there's little possibility of kinking them or folding them back. In critical applications like the military and aerospace, they are required.

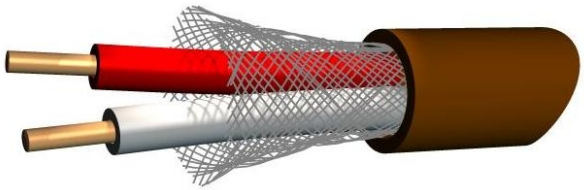


PHOENIX CONNECTORS

These don't involve soldering or crimping – you just stick the wire in the hole and crank on the screw. Very easy, especially for field installation. I shouldn't be calling them “Phoenix” connectors; that's a brand name, but that's what most people call them. It's important to strip the wire right, insert it correctly, and crank down properly. Takes practice. You should do it.

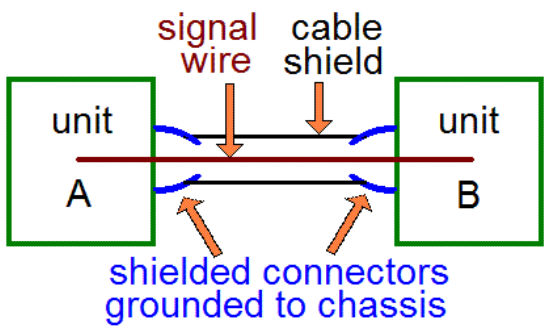
SHIELDED CONNECTORS

In a shielded cable, one or more signal conductors are completely surrounded by a wire or foil **shield**. If there's only one signal wire, the cable is called **coaxial**, or **coax** for short, because the signal wire and shield are on the same axis. Shielded cable with more signal wires is not coaxial, strictly speaking, though many people call any shielded cable “coax.”



The purpose of the shield is to block electrostatic signals coming in or going out – that is, to prevent the signal wires from accidentally picking up external electrostatic interference, or radiating it. Since the shield is non-ferrous (contains no iron), it does nothing to stop the other kind of radiation, which is electromagnetic. However, by running the signal wires inside the shield, the cable's magnetic field is confined, so a coax cable stops electromagnetic interference too.

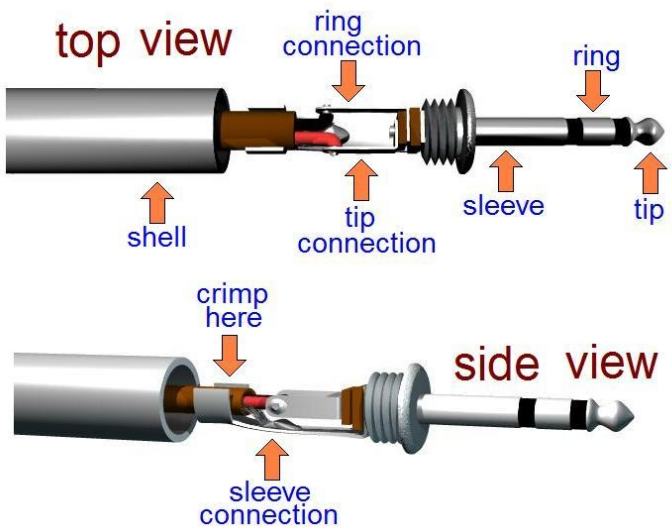
A shield only does its job if it is connected to the chassis grounds of the equipment it works with. The purpose of a shielded connector is to carry the protective shielding through the connection point, and to electrically connect the shield to chassis ground. Thus the signal travels in a safe, protected environment from the insides of one unit to the insides of the other.



Shielding isn't perfect; some signal can push its way in or leak out. In fact, one way of sprinkling an RF signal over a large area (a drive-in movie theater for example) is to deliberately choose a coax with a loose shield to carry the signal around. Braided shields vary in their tightness, and some cables have two or even four layers of shielding.

AUDIO CONNECTORS - 1/4" PHONE PLUG / JACK

These are called "phone" plugs because they originated in the telephone business. The main body of the plug is the **sleeve**, which is grounded. If the cable is shielded, the shield connects to the sleeve. The ball or bullet on the end is the **tip**, which carries the signal. In many cases there's a separate **ring** behind the tip, which is used for a second signal path.



There are one or two solder lugs at the back of the plug, and a ground connection which is also cable support and strain relief. Once the cable is connected, a **shell** covers the back end and the connections.

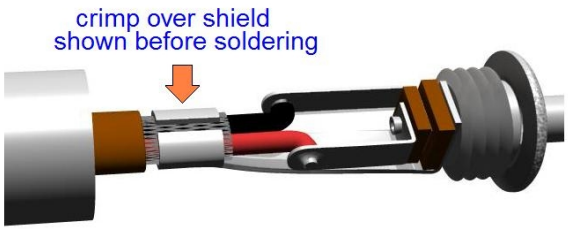
Installing a phone plug:

- Insert the cable through the shell.
- Strip off just enough outer jacket that, when the strain relief is clamped on, it will clamp over the insulation and the signal wires will be long enough to reach their connections.
- Unthread the braid and pull to one side.
- Solder the braid to the sleeve connection. Be sure it's cut short enough that it can't come in contact with the signal terminals, even if the part it's attached to is flexed. In the illustration to the left, there is a danger that the shield could short to the signal connections. If necessary, fold the braid back under the jacket and solder it there.
- Insert the wires into the tip and ring connections and solder.
- Crip the strain relief over the jacket.

I've never been much impressed with the kind of strain relief that crimps over the jacket. No matter how hard you crimp it, it's still possible to pull the cable backward. The real strain relief is the shield, which can stand a lot more pulling than the signal wires can.

When you're preparing the signal wire or wires for soldering, you should try to leave a tiny bit of slack in them so the shield, not the signal wires, will absorb the stress when the cable is pulled. The best plugs also have rubber strain reliefs at the back.

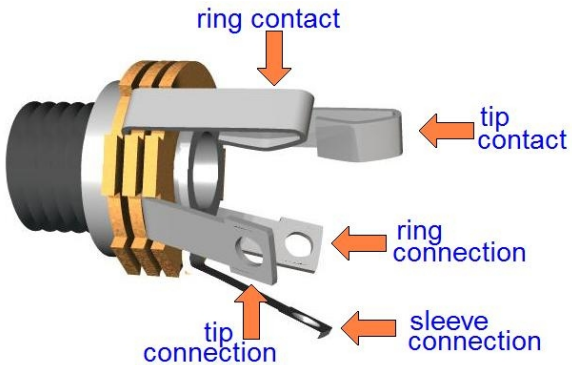
Some people like to strip the jacket back a little further, crimp the strain relief over the braid, and then flow-solder the braid to the strain relief.



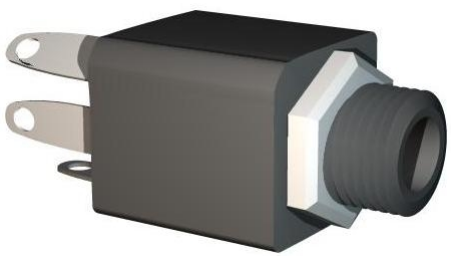
There is no doubt that this is makes for a stronger cable, but all that heat can melt the inner insulation and short the signal wires to the braid. If you want to use this method, great care and a lot of practice will be necessary. Use whichever method works best with the cable you're using.

¼" plugs made by Neutrik work differently; the plug is inserted into the shell from behind.

Most jacks are chassis-mounted, with a threaded shank that pokes through a hole. If you look at the back, it will be obvious which terminal connects to the shank, which then connects to the plug's sleeve (ground). Chassis-mount jacks come with lockwashers. Use them, or the jacks will come loose.



Some jacks have plastic outer shanks, as shown below. The reason for that is because you want to ground the sleeve, but maybe not right at that point. For one thing, the circuit inside a unit is usually chassis-grounded at the power supply, and if the jacks were also chassis-grounded, that would create an internal ground loop. This is discussed in greater detail in the EM3 study guide. The important thing from an installation standpoint is that you can't crank the nut down on those plastic threads very hard or you'll strip them. Instead, I add a drop of gel-type liquid thread locker as made by Loc-Tite and others. Super glue will do in a pinch.



There is almost no such thing as a ¼" chassis-mount plug; they're all jacks. This means a cable designed to connect two pieces of equipment, called a **patch cord**, is almost always plug-to-plug.

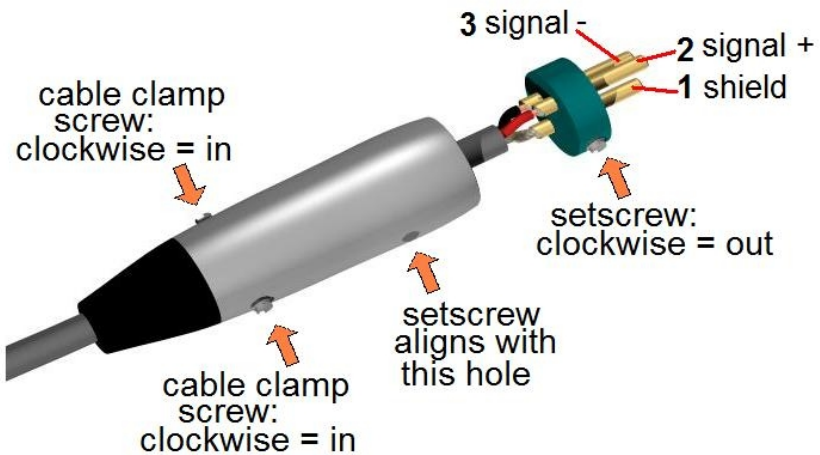
1/8" (3.5mm) plugs and jacks are just ¼" plugs and jacks on a starvation diet. The techniques are the same, though the dexterity required is greater. JFYI, when plugging or unplugging a phone plug, there's a moment when it shorts. Think twice before using it in a high-power circuit.

XLR CONNECTORS

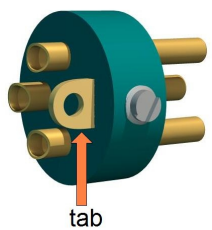
Professional 3-pin audio connectors are intended for balanced signals, which means shielded twisted-pair cable. Pin 1 is the shield, pin 2 is plus, pin 3 is minus. (The green insert has numbers molded into it.) This is a case where it's important not to strip off too much of the jacket, because the strain relief has to be able to clamp onto it.

Note that the pin pattern is not the same as with a power outlet, with the ground in the middle! XLR connectors were developed back when power outlets only had two prongs, and they're not related.

The two most common types are made by Switchcraft and Neutrik, and their Chinese imitators. The Switchcraft type has three screws. Two of them press on metal pieces that clamp down on the cable jacket. The third secures the connector part in place. This is a reverse-thread screw that comes outward when turned clockwise. That way, you screw all three counterclockwise to take the connector apart and clockwise to put it together.


3 signal -
2 signal +
1 shield
cable clamp screw: clockwise = in
setscrew: clockwise = out
setscrew aligns with this hole
cable clamp screw: clockwise = in

A Switchcraft XLR connector has a solder tab that connects to the screw that connects to the shell. As a rule, this should not be connected to any part of the cable.



Neutrik XLR connector is pushed into the shell from behind, like their ¼" connector. Again, the shield should be cut a little shorter than the signal wires, so if the cable is yanked on the shield takes the strain.

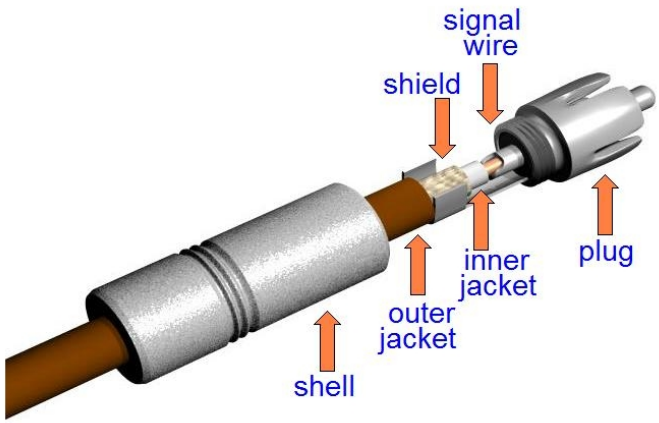
When an XLR cable is used with an unbalanced signal, pin 3 may need to be connected to pin 1 – or not! This is an important issue and a continuing problem in audio, and should not be treated lightly. This topic is covered in more detail in the EM3 study guide.

Signal flows in the direction of the pins: outputs are plugs and inputs are jacks. Once in a while you'll find a sound system where the inputs are wall-mounted plugs, requiring jack-to-jack cords. This is done because the wall plug is harder to vandalize. The consensus nowadays seems to be that this causes more problems than it solves.

RCA PLUG / JACK

This is also called a **phono plug** because RCA, which was once the 600lb gorilla of consumer electronics, invented it to connect a phonograph to a radio. Note the difference between the RCA "phono" plug and the ¼" "phone" plug.

In most cases, you insert the signal wire and solder from the back. This works a whole lot better if you clamp the outer part in a small bench vise. (Don't clamp it hard enough to warp it!) The shield must be shorter than the signal wire because it solders further back on the plug than the signal wire. The illustration below shows the process before the clamp is crimped around the shield and before the shield and signal wire are soldered.



RCA plugs and jacks aren't just used for audio, they're also used for RF and composite video, for which they are not well suited – but they're cheap, common and fairly reliable, and that counts for a lot. As a rule, the plastic insulator in an RCA jack will be white for left-channel audio, red for right-channel audio and yellow for composite video.

In an audio system, when plugging and unplugging RCA connectors, the signal channel should be turned down or off. The tip connects before the shell, meaning there's a moment when the signal wire is connected but the ground is not. In an audio system, that causes a mondo-mega-gigantic “BRAAAAP” that may blow a speaker out. Turn down the gain before plugging or unplugging.

An RCA connector usually indicates an audio signal that's fairly high impedance, meaning the capacitance of a long cable can attenuate high frequencies. With a high impedance signal, a cable over 25 feet long may shave off the high frequencies a bit. You may want to check out the impedance-changing transformers available.

RADIO FREQUENCY CONNECTORS

The most important way an RF connector differs from those used for lower frequencies is that the connector itself is designed with impedance in mind.

We have to make a distinction between “RF,” as in radio frequency, and video. Video signals, especially modulated ones, are radio-frequency signals. However, like old European royalty, video doesn't mix with the rest of the RF world. With few exceptions, video systems are 75Ω, while other RF systems are 50Ω.

UHF / 259 / M CONNECTOR

A 50Ω connector designed in the 1930s, large and clumsy but well established and widely used, especially at high power levels. The plug is known as a PL259 and the jack or socket is called a SO259. They screw together via internal threads on the plug and external threads on the socket. Note the insane size of the signal pin. The PL259 was intended as a banana plug with shielding; the pin size is 4mm like a banana plug.

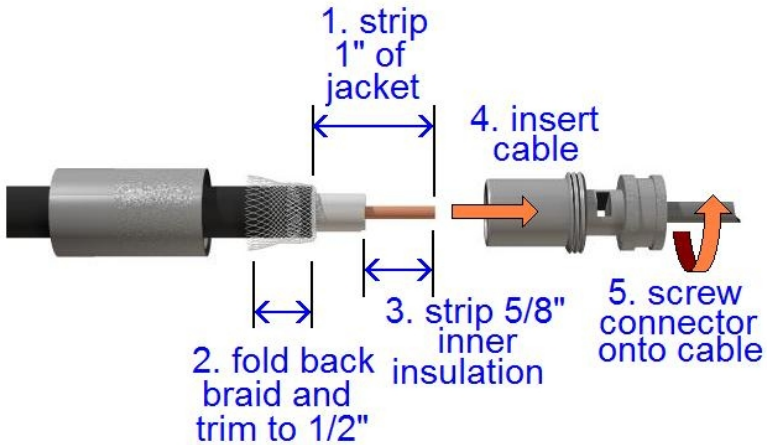
It's called a UHF connector, but in the 1930s, “UHF” meant anything over 30MHz. It's actually only good to about 150MHz because the impedance dips to around 30Ω in the center of the connector; the higher the frequency, the more reflection problems that causes. (There's a deluxe version that's good to about 450MHz.) It's still widely used, especially by radio amateurs and in marine applications, for two reasons. One, you don't need special tools to install it. Two, it's really rugged.

The very ruggedness that makes the PL259 popular also makes it a bear to install. With large RG-8 or RG-9 cable, you will *not* do a good job the first time. If you're going to work with these connectors, you'll need to practice. And it should go without saying that you don't do your first one on the jobsite, with the customer watching.

Start by taking the shell off the inner part of the connector. In most cases, you'll have to screw it off. Slip the shell over the end of the cable.

Next, follow these steps in order:

1. Strip off an inch of outer jacket.
2. Fold the braid backwards over the jacket and trim to ½" length. If there's a layer of foil too, cut it off right where it comes out of the jacket.
3. Strip off $^{5}/_{8}$" of the inner insulation, leaving $^{3}/_{8}$" insulation sticking out.
4. Insert the cable end into the inner part of the connector.
5. Screw the connector directly onto the cable. The screw threads inside make reliable connection with the braid.



At this point the signal wire should almost be poking out the end of the tip. (If it is poking out, cut it off flush.) Clamp the main part of the connector lightly in a vise. Hold a soldering iron against the side of the tip and apply solder to the open end. (If you're too stubborn to use a vise, and hold it in your hand, this is where you learn how quickly heat spreads from one part of a connector to the other parts.) Let a fair amount of solder wick in so you're sure you have a good connection. Try not to let solder run onto the side of the tip; if it does, hold the soldering iron under the tip to draw the liquid solder off. You don't want solder to increase the tip diameter. Once you've got the tip soldered, clean off the flux. Paint thinner works fine, but a well-stocked shop will have flux remover around.

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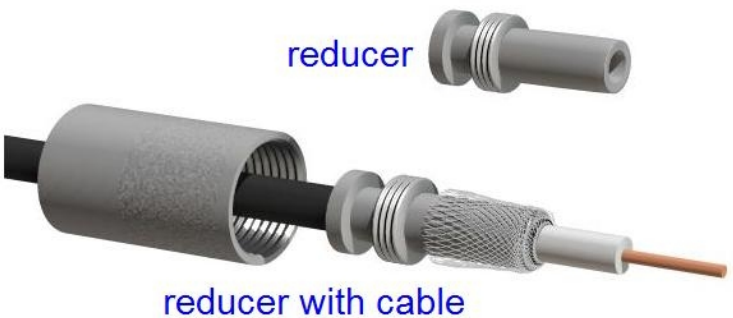
Some people don't trust the threaded connection to the braid. If you're using copper-braid cable, you can get a PL259 connector with holes in the side. Use a big iron to heat up the inner part of the connector, then apply solder through the holes. This results in a sweat-soldered connection between braid and connector. Test the cable first to be sure it can handle that much heat – cable with inner insulation made of foam will usually melt and be ruined.

At this point, all you have to do is screw the shell onto the front part of the connector, test the cable, and you're done.

RG-8 and RG-9 cables do not all have exactly the same jacket diameter. You may find that a certain brand of cable simply cannot be screwed into a certain brand of connector. You'd think after about 80 years, all this stuff would be standardized, but it's not. When you're out in the real world, the shop you work for will have selected cable and connector brands that work together. Problem solved, almost. Sometimes you'll run out of one or the other, and you'll have to use a substitute. Try it out before you buy a bunch. ("Test it first" is always a good rule of thumb, no matter what you're doing.)

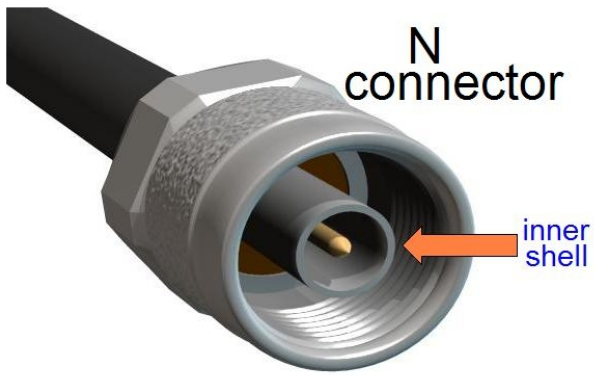
To use a PL259 with smaller cable such as RG-58, a reducer is required. Put the reducer over the cable first thing. Then prepare the cable end in the normal fashion, but cut the braid off short enough that it cannot reach the reducer's threads. Put cable end and reducer into the front part of the connector and screw in. In the illustration, I've shown the shell over the cable, but when using a reducer, you don't always have to disassemble the PL259 first. The reducer and cable can often be inserted into the back of the connector with the shell in place.



The chassis-mounted connector, the SO239, is much easier. Up to a few MHz, you don't have to pay much attention to wire lengths etc. With RF connectors especially, a chassis mounting may be called a **bulkhead** mounting.

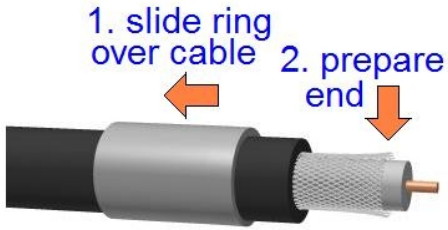
N CONNECTOR

Electronic stuff tends to get smaller and more efficient as time goes on. In the 1940s, a smaller cousin of the PL259 was invented called the **N connector**.



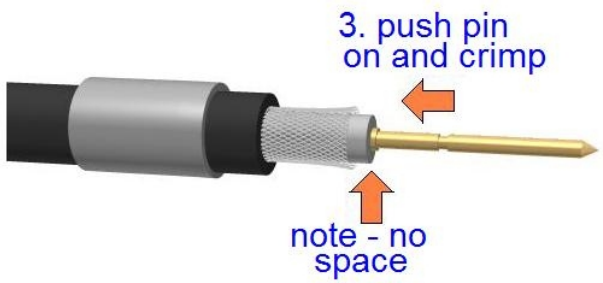
The N connector introduced an important innovation: the inner shell. This separated the screw-on attachment function from the signal-conveying function, and enabled much better control of impedance. As a result, the N connector was the first “real” high-frequency connector, good to at least 10GHz. (Deluxe versions today are good to 18GHz.) Most N connectors are 50Ω. Patching 50Ω and 75Ω connectors together is not recommended; besides the impedance mismatch, the pins are different diameters and the connectors may be damaged.

The most common type of N connector comes in a package with the signal pin, shell and crimping ring. (Manufacturers like to get all fancy and call the ring a “ferrule.” I'll stick to “ring.”)

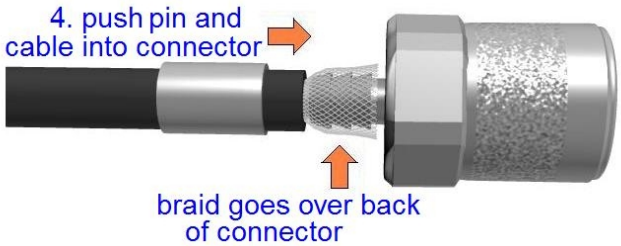


The ring is first slipped over the cable, then the cable end is prepared according to manufacturer's instructions. It is very important to measure precisely.

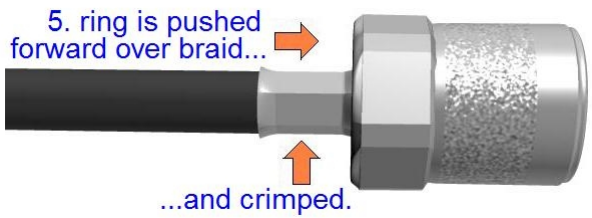
The pin is then pushed onto the signal wire and crimped. The pin should butt up against the inner insulation. Why should that matter, you ask, since it's insulation and nonconductive? Because insulation has dielectric properties, which matter even if it doesn't conduct. By butting the pin up against the insulation, disturbance of the impedance is reduced.



After the pin is crimped, flare the braid a little, then push the pin and signal wire into the connector. If everything has been measured right, the pin will seat and lock with a “click.” At the same time, the braid slides over a ribbed section at the back of the connector.



The crimping ring is then slipped over the shield and crimped on six sides.



All this crimping requires a tool made for the purpose. Sometimes, when I haven't had the tool available, I've had to try other crimping methods, and none of them are much good. There's just no substitute for the right tool. The tool is expensive, and may be hard to justify. Some manufacturers make versions you can solder instead of crimping. Naturally, these have to be used with copper-braid cable, since you can't solder an aluminum braid.

There are also N connectors with threaded back ends that simply screw on over the cable shield, like a PL259. They're fine, but you don't want to use them for cables that will be frequently plugged and unplugged.

The most critical thing about installing an N connector is stripping the outer and inner parts of the cable to the correct lengths. If you do it wrong, the connector simply won't work. I won't say anything specific because different manufacturers require different cable preparation. Every manufacturer offers detailed instructions. Follow them carefully.

BNC CONNECTOR

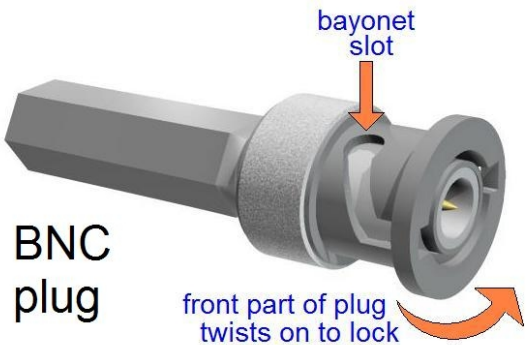
BNC connectors are very widely used in RF circuits, video and test equipment. Most are 50Ω but 75Ω versions are available. Below 10MHz the mismatch isn't significant, but at higher frequencies you have to be sure you're using a BNC connector with the same impedance as the cable. The 50Ω version is good to 4GHz and the 75Ω version to 2GHz. Many people are in the habit of using 75Ω cable along with 50Ω connectors for video, which isn't a problem unless you're dealing with very high definition.

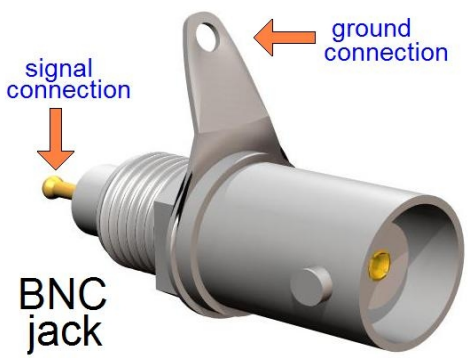
There are versions available for RG-6 / RG-8, RG-58 / RG59, and miniature cables like RG-179 and RG-316.

The inner shell and pin of a BNC connector are the same as an N connector. The reason it exists is to permit simpler, quicker connection and disconnection than with the N connector. (That's one of the reasons it's so popular in test equipment.)

The “B” means “bayonet.” There are a pair of pins on the side of the jack, and you plug the connector in by pushing and twisting the way you do with the tail light in a car.

Most BNCs have ribbed back ends and crimp rings, but in the illustration to the right I've shown one where a threaded inside screws onto the cable braid, like a PL259.

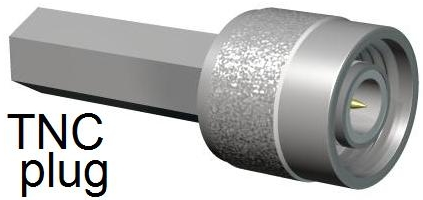




Cable connectors are almost always plugs; chassis connectors are jacks.

TNC CONNECTOR

At the highest frequencies, BNC connectors create noise when wiggled and they leak signal. The TNC connector is a BNC connector with a screw-on shell instead of bayonet slots – the “T” means “threaded.” It contains the signal much better and also works at higher frequencies, more than 10GHz.



You're thinking, “but there's already a threaded N connector, why don't people just use that?” Lots of people do. But a TNC connector is more compact and in many cases smaller is better. The same reason cellphones have micro-USB ports instead of the full-sized kind.

The inner pin and barrel of N, BNC and TNC connectors are all the same. In shops where all three kinds show up, techs sometimes cut off the outer shells on their test probes and just use the inner parts as push-in connectors. This is perfectly legitimate up to a few hundred MHz, as long as you remember that you're going to get leakage and noise you wouldn't get with a “legit” connector.

I think we'll be using N / BNC / TNC connectors for a long time, because at high frequencies, the electrical characteristics of a cable or connector are dictated by its physical dimensions, and any good 50Ω connector automatically has to be a lot like an N / BNC / TNC connector.

MOTOROLA CONNECTOR

Motorola began as a car-radio manufacturer in the 1920s – that's why it's called "Motor"ola – and their antenna connector is still used with car radios. This connector is unusual because the whole plug goes inside the jack. Two springy parts that stick out on either side of the body wedge the connector in place and provide ground contacts. Note the hole in the end of the tip. This is where solder is applied.

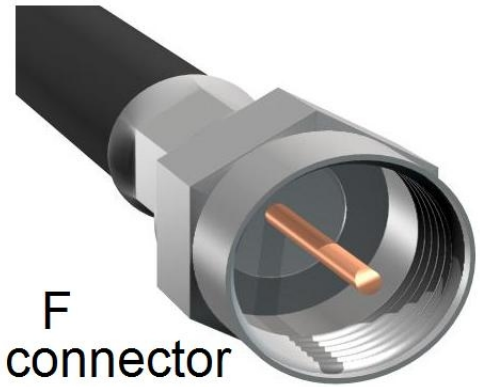
- Prepare cable end. Note the unusually long exposed inner insulation and signal wire.
- Insert into connector.
- Sweat-solder tip. Apply iron to side of tip and solder to end hole; let a generous amount wick in.
- Solder back end to shield.

The connector is designed to go over the braid, but sometimes you'll have to put the braid over the connector. In that case, use the shortest braid you can get away with, or it may bump up against the outside of the jack and stop you from plugging the cable in. A short length of shrink tubing over the back neatens things up a lot. Don't put shrink tubing up over the parts that stick out from the sides, as these are the ground connections.

F CONNECTOR

One of the problems with RF connectors is that the signal pin represents an unavoidable bump in the impedance. The F connector mostly solves the problem: it doesn't have a signal pin. Instead, the inner conductor of the coax itself is used for the purpose. This also makes it inexpensive and easy to assemble.

The “F” connector is a coaxial connector intended for video, so it has a 75Ω impedance, and it works well to several GHz. The plug has a screw-on cap that mates with threads on the outside of the jack. Cable-end connectors are almost always plugs; bulkhead connectors are almost always jacks. If you need to join two cables, you buy an adapter.



The signal wire must be solid and stiff. In most RF coax, the signal wire is steel with a copper cladding. That seems cheap, but in fact there's little reason to use a solid-copper conductor, since skin effect pushes the signal to the surface at these frequencies. And steel gives the F connector a nice sturdy wire to use as the signal pin.

F connectors are used with 75Ω RG-59 or RG-6 cable. The industry has been tending toward the larger-diameter RG-6 due to the increasing bandwidth demands of hi-def TV and RG-6's less severe high-frequency loss.

RF coax cable shields are often aluminum, so they can't be soldered. For this reason, in many if not most F connectors the shield is connected by crimping. There are so many connector variations that I can only say, use the proper tool and study the manufacturer's instructions.

You have to pay attention to which connector you're getting. Belden, for example, offers five different F connectors for use with:

- RG-59
- quad shielded RG-59
- RG-6
- quad shielded RG-6
- RG6 universal

Each brand of connector has its own requirements regarding length of stripped conductors etc and usually its own type of crimping tool.

There's a “quick” F connector without threads that just pushes onto the jack the way an RCA plug does. These work fine, but of course if there's any pull on the cable they'll come unplugged.

Standard F connectors are not waterproof. If you're installing a system that uses F connectors outdoors (e.g. to connect to an antenna) use special water-resistant connectors and be sure to use a drip loop.

RCA AGAIN

RCA connectors are not RF connectors, but try to tell that to the people who use them that way. Composite analog video (where all parts of a baseband video signal are combined on one signal wire) uses RCA connectors, usually with yellow inserts to tell you they're video. This doesn't make much sense, since the F connector is far better and costs less. But RCA is an established standard for consumer-grade analog video. RCA connectors are also found in various kinds of RF gear, like amateur radio equipment. Under 10MHz, they work okay.

TELEPHONE-STANDARD 25-PAIR CABLE

There are cables with paired wires (and for that matter, unpaired wires) with many color schemes, but one you'll run into often was originally developed for land-line telephones. I've put it under a separate heading because there's no single connector type for it. It's used today for all kinds of communication. Why? Cuz it's cheap and simple to work with, that's why. We like cheap. And we like simple. Let's hear it for simple. Yay, simple.

A phone line consists of two wires, twisted around each other to reduce signal leakage from one line to another (called **crosstalk**). The insulation on one wire is a certain color with a stripe of a second color. On the other wire, the insulation is the second color with a stripe of the first color. That shows they belong with each other. For example, pair number one has a wire that's white with a blue stripe and a wire that's blue with a white stripe. The wires are called **tip** and **ring** respectively, which we'll talk about shortly.

It works a lot like counting numbers, except we're used to having ten numbers. In the wiring code, there are 5 major colors and 5 minor colors.

MAJOR	MINOR
white	blue
red	orange
black	green
yellow	brown
gray or slate	violet or purple

You go through the minor colors first:

PAIR	MAJOR COLOR	MINOR COLOR
1	white	blue
2	white	orange
3	white	green
4	white	blue
5	white	purple

Then you go to the next major color, and go through the minor colors again:

PAIR	MAJOR COLOR	MINOR COLOR
6	red	blue
7	red	orange
8	red	green
9	red	brown
10	red	purple

This continues until you get to the last pair:

PAIR	MAJOR COLOR	MINOR COLOR
21	gray	blue
22	gray	orange
23	gray	green
24	gray	brown
25	gray	purple

In other words, the POTS color code provides for up to 25 pairs. You can find a complete, printable chart in the review chapter.

In a cable with more pairs, you'll find groups of 25 loosely wound with silk thread in the minor colors. For example, a 100-pair cable will have 25 pairs wound with blue, 25 more pairs wound with orange, 25 pairs wound with green, and 25 pairs wound with brown.

You'll also usually find a nylon string running the length of the cable. After you make about a 2” slit at the end of the jacket, you can fish out this string and pull it sideways to rip the jacket open. This is handy because standard 25-pair telephone connection blocks require stripping off more than a foot of jacket.

In a cable with fewer pairs, the code is followed as far as it goes. For example, in a 12-pair cable, the last pair would be black / orange.

As mentioned, this color code is not limited to telephone use; you're likely to find it wherever there are lots of unshielded twisted pairs. CAT5 and CAT6 cables, for example, use the first four pairs.

Note that this color order has nothing in common with resistor color codes, it's an entirely different system. Note also that not every UTP cable used in every branch of electronics follows this code. But in the telephone and telecommunications world, it's practically mandated by law.

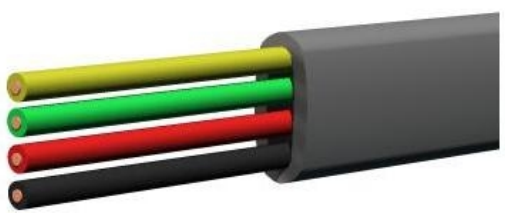
Many connectors designed for this kind of cable, e.g. 8P8C modular connectors, do not require stripping the wire ends. The connectors use **insulation displacement** contacts, in which sharp metal edges cut through the wires' insulation and make contact with the wires.

Tip and Ring

Most telephones are designed so line polarity doesn't matter, but there are some applications where, if you flip the polarity of a pair, the system won't work. And in data cables like CAT6, polarity must be correct. If you don't pay attention to polarity, at the very least other techs will think of you as a careless jerk.

You've seen old pictures of women in long skirts sitting at telephone switchboards, patching and unpatching telephone lines that terminated in plugs. Those were ¼" 3-circuit plugs. We use the same kind of plugs today for guitars and audio patch cords. The tip was connected to the ground-side telephone wire, which is the first wire in a pair, e.g. white with blue stripe. The ring was connected to the wire with -48VDC on it, e.g. blue with white stripe. We still call these wires tip and ring to this day.

There's another kind of telephone cable called **station wire** that is not striped. It has two pairs, usually not twisted; in normal use station wire runs are not long enough to create crosstalk problems so twisting is not needed. Station wire can be round or flat.



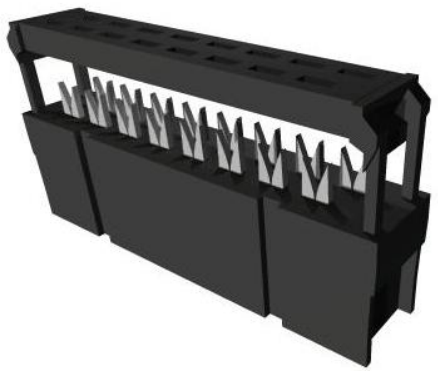
The code is:

Pair 1 tip	green
Pair 1 ring	red
Pair 2 tip	black
Pair 2 ring	white

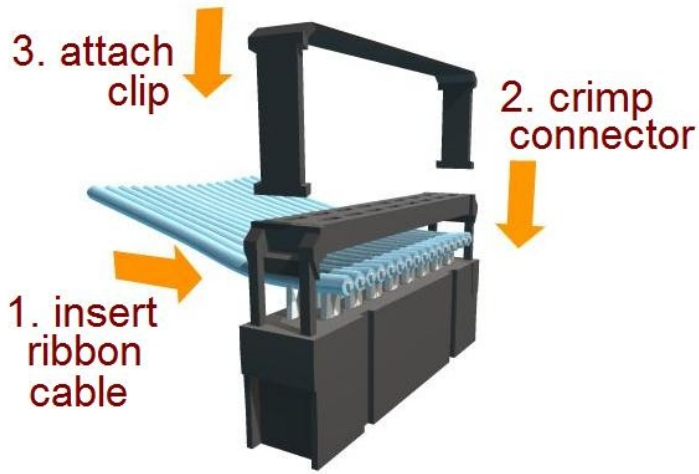
Warning: in land-line phones where only one pair is used, the other pair may carry DC from a local power supply. Know what you're dealing with.

MASS CONNECTION

"Mass Connection" usually means "ribbon cable," the insulation-displacement idea applied to as many as 64 wires at once. The connector has two staggered rows of forked contacts that cut through the insulation and make contact with the wires.



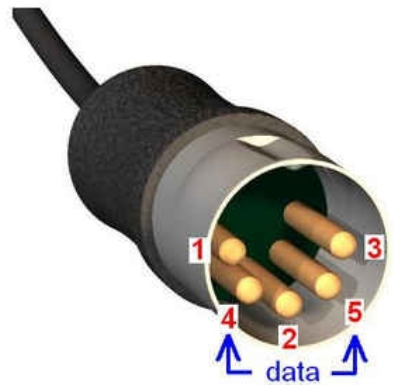
Installing the connector is a 3-step process. First, insert the connector in the tool and put the ribbon cable into it. Be sure you have the connector oriented the right way; they're polarized. Second, clamp down on the tool to crimp the wires onto the contacts. With most brands, there should be a definite click. Third, attach the clip that holds everything in place. Again, there should be a click. When you go to put the other end on, visually trace one of the wires from one connector to the other. Ribbon connectors can go on backwards or forwards, right side up or upside down, so you have to pay attention.



MIDI

Traditional MIDI uses a 5-pin DIN connector. Note that the pins are numbered differently than you'd expect – that's because not all DIN plugs have five pins. Midi uses pins 4 and 5, which is a safety feature. At the time MIDI was invented, lots of audio equipment used DIN connectors for signal. (That's what the DIN plug was designed for.) The two stereo channels and shield were on pins 1, 2 and 3. DIN uses pins 4 and 5 to lessen the chance of blowing up an audio circuit.

There are two 5-pin DIN patterns; one based on a 180 degree arc and one on a 240 degree arc. You want the 90 degree one.



USB, FIREWIRE, THUNDERBOLT

Short, sweet and simple (yay, we like simple): don't try to build these cables. At the high frequencies involved, the tiniest details, like the size of a solder blob, can cause impedance hiccups and reflections. If your career takes you to where you need to build these cables, you'll get special training.

End of Chapter 9

EM5 Chapter 9
MAKING MEASUREMENTS

Objectives of this chapter:

- *define multimeter, VOM, oscilloscope, function generator*
- *list the kinds of things a VOM measures, and typical ranges for each*
- *explain how to properly connect a VOM when making voltage, current (direct and indirect) and resistance*
- *list precautions when making each of the above*
- *explain meter loading, ohms per volt*
- *list special precautions when measuring AC*
- *explain the function of the attenuator switch in an oscilloscope probe*
- *explain how to calibrate a scope probe*
- *explain how to properly set the horizontal and vertical range switches of an oscilloscope*
- *explain how an oscilloscope may fail to display certain events, based on how its controls are set*
- *explain how to detect and correct this problem*
- *describe the purpose of each control on a function generator*
- *define modulation and describe how two function generators can be arranged to produce it*
- *discuss limits to accuracy and resolution*

We've looked at a number of common signals, now let's take a closer look at how to measure them. We're going to concentrate on the **multimeter** and the **oscilloscope**, which techs use more than all other test gear combined. We're also going to discuss the most widely flexible signal source, the **function generator**. Those three items are all the test equipment many techs ever need.

I'm going to do something a little strange. I've already described these three pieces of test gear in EM1 and EM2, and I could just cut and paste, but instead I'm going to write whole new descriptions. One, it seems kind of lazy to just lift stuff from another study guide. Two, these items are important enough that it's worth describing them two different ways. Something might click that didn't before. Three, you have more knowledge now. This will give me a chance to alert you to some booby traps, which you wouldn't have understood before, that beginning techs usually spend their first couple of work years tripping over.

To repeat something I mentioned in EM1: a tech should get in the habit of visualizing voltages and current flows. You should get to the point where you can almost see the little green electrons (or little red holes, if you're a conventional-current person) bumping along the current paths like marbles or Pac-Men or whatever. It's really helpful.

And one more repetition: become very, very familiar with your test gear, its quirks and limitations. When you get a reading that isn't what it's supposed to be, you want to be confident that it's because the equipment you're working on is really broken, not because you're making the measurement incorrectly. Otherwise, you can waste a huge amount of time trying to figure out why a measurement seems to be wrong, when the problem is actually somewhere else in the circuit. One of the *most common errors I see beginning techs make* is to innocently accept an instrument reading that should be sending up red flags.

THE MULTIMETER

By far the most-used measurement tool is the common **multimeter**, also known as the **volt-ohmmeter** or **VOM**. At a minimum, it measures DC voltage, AC voltage, DC current, and resistance. Since it measures current, it probably should be called a VOAM, but for some reason it almost never is.

To the right is shown a typical inexpensive VOM. The large knob is the **function switch**, which allows users to choose what they're measuring. This particular meter measures:

- DC Voltage
- AC Voltage
- DC Current
- Resistance
- Diode operation
- Transistor gain
- Continuity

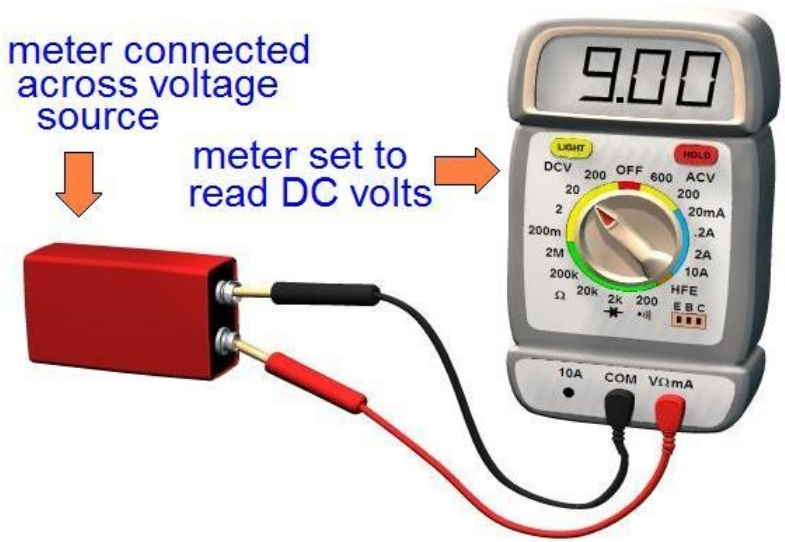
The meter also has two convenience features: a HOLD button that captures a reading, permitting you to watch what you're doing when you're making a measurement, instead of looking at the display, and a LIGHT button that lights up the display when you're making a measurement in a dark place.

MULTIMETER MEASUREMENTS

How you measure depends on *what* you're measuring; you attach the test leads differently for different measurements.

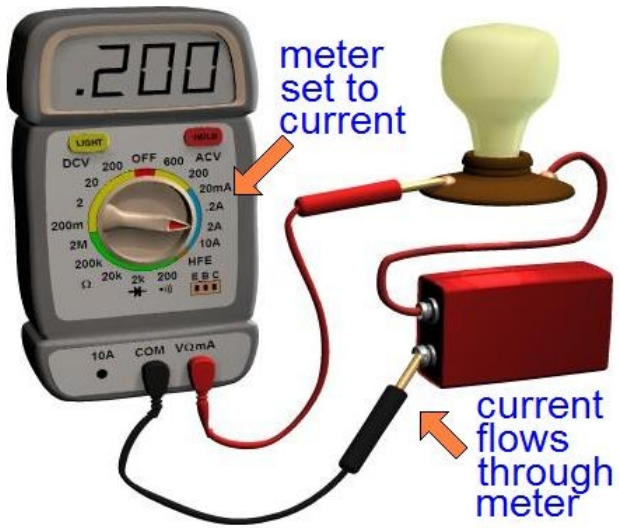
Measuring Voltage

To use the VOM as a voltmeter, the equipment you're testing must be “on,” that is, powered up. The meter probes are attached across the voltage you want to measure.

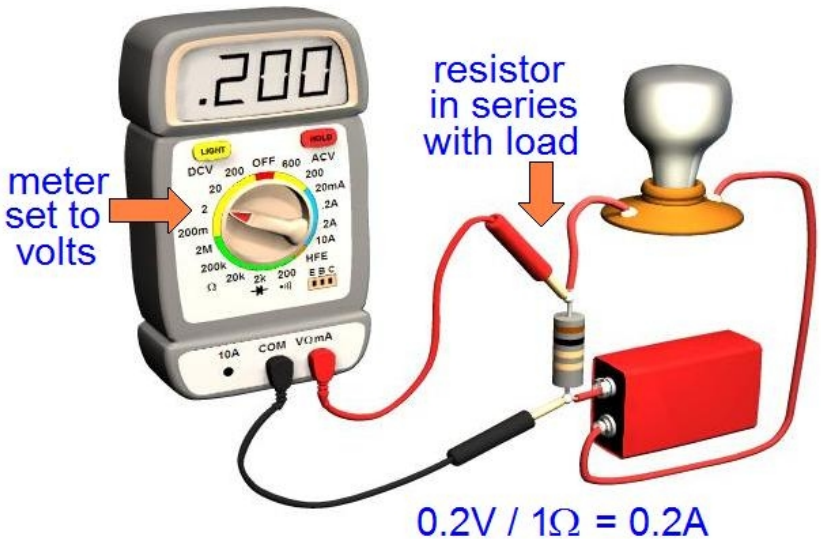


Measuring Current

To use the VOM as an ammeter, the meter must be connected into the circuit, so current flows through it. The equipment you're testing must be “on,” that is, powered up.



That's the direct method of current measurement. There's also an indirect way to measure current: insert a low-value resistor, measure the voltage drop across it, and use Ohm's Law to calculate current. In this case (next page), we have a 1Ω resistor and a 0.2V drop. That's 0.2A.



This is pretty much how most current-measuring meters work anyway, with a low-value resistor inside the meter. You're just doing the same thing, placing the resistor outside the meter. “Low value” means a resistance that's high enough to develop measurable voltage drop, but not enough voltage drop to affect the equipment's operation. This resistor is called a **shunt**.

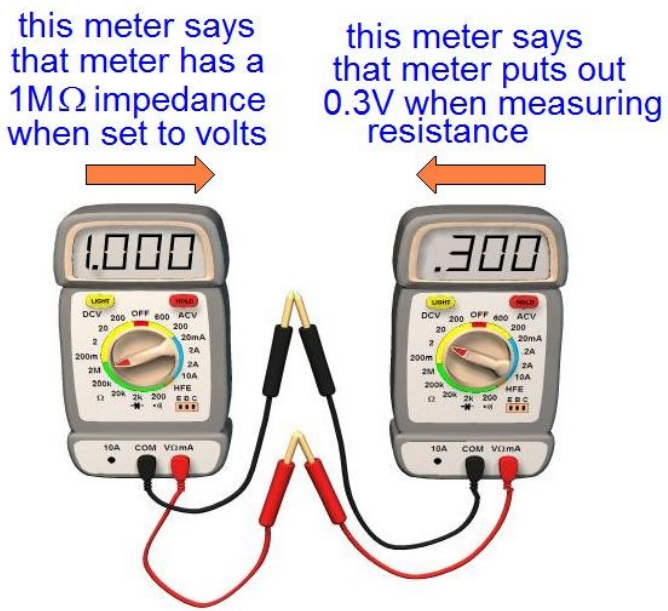
Measuring Resistance

For resistance, the meter is connected across the resistor being measured. A battery in the meter puts a small voltage across the resistor and measures the current that results. The equipment must be “off,” powered down, and large capacitors must be discharged. An ohmmeter is essentially a voltmeter with its own voltage source; any other voltage source in the circuit will throw the measurement off.

When measuring the resistance of a part while it's in the circuit, remember that there are other parts connected. Just because you have the test leads across a particular part doesn't mean you're only measuring that part. This is where a deep knowledge of circuits and components comes in handy. You may have to unsolder one end of a part and bend it up, away from the board, to measure it by itself. This won't work with surface-mount parts, you'll crack them. They may have to be completely removed. It may be easier to power the unit up and make a lot of voltage measurements, then use Ohm's Law to calculate values and zero in on a particular resistor's value.

If the voltage coming out of the meter is 0.7V or greater, that will forward-bias any diode (or transistor junction) in the circuit. You can tell this is happening if the reading changes when you change ranges. For example, if the reading is 100Ω when you have the meter set to the 200Ω scale, but 800Ω on the 2kΩ scale and 6kΩ on the 20kΩ scale, you're seeing the effect of a nonlinear component like a diode.

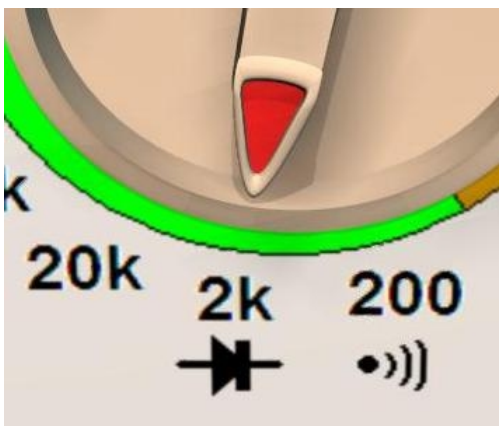
It's easy enough to find out what voltage the meter uses to measure resistance: just connect another meter, set to read voltage. Most digital ohmmeters put out around 0.3V, which isn't enough to forward-bias a diode.


this meter says that meter has a 1MΩ impedance when set to volts
this meter says that meter puts out 0.3V when measuring resistance
1.000
.300

What if the Ohmmeter starts out at one reading, and slowly changes to another? There is a large capacitor in the circuit and the Ohmmeter's voltage is charging it up. Wait for the reading to stabilize and then make the measurement.

Measuring Diode Operation

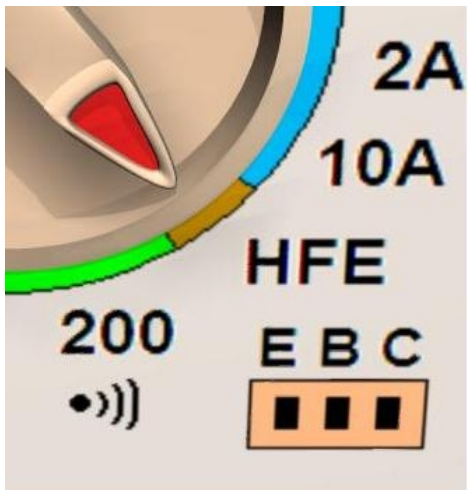
The diode scale uses the Ohmmeter circuit, but it's calibrated so the reading shows the forward voltage drop. A reading of 0.6V to 0.7V means the diode is good.



You can use this function to check diode polarity. In about 99% of VOMs, the resistance and diode-check functions put the positive voltage on the red wire. A diode becomes forward-biased – it conducts – when the positive voltage is connected to the diode's anode.

This also works for testing the junctions of a transistor.

Measuring Transistor Gain



To measure gain, the meter applies a small current through the transistor's base and the measurement shows the resulting current through the collector as a multiple of base current, e.g. 100X for a transistor with a beta of 100. This is quite a crude measurement, and would vary a lot if different voltages and currents were used. But it does permit you to see if a transistor is OK and what its general gain range is.

Measuring Continuity

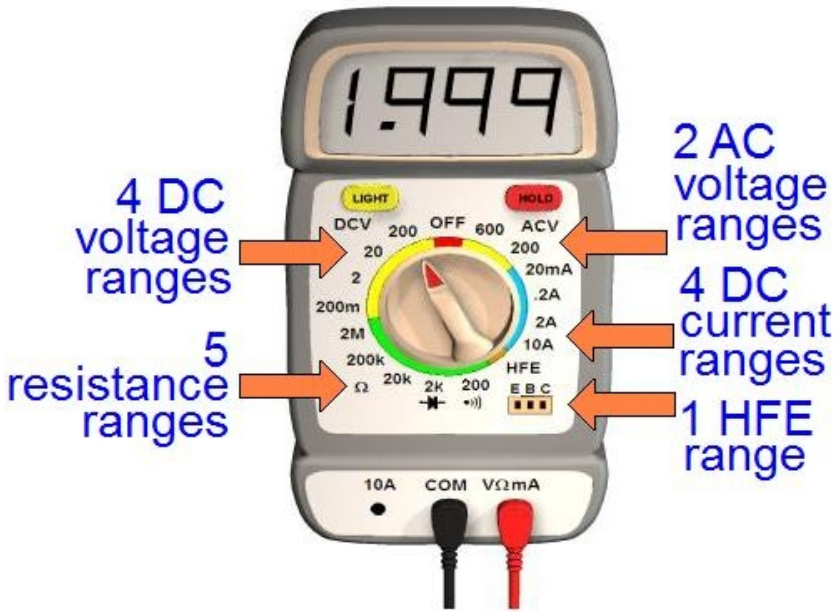
Saying something has “continuity” means there's a current path, a continuous circuit. This is a quick measurement that tells you if, for example, a cable is good, open, or shorted. When the meter senses continuity, it beeps. Handy, that: you don't even have to look. Somewhere between a short circuit, where the continuity function beeps, and an open circuit, where it doesn't, there has to be a dividing line. If you really want to know your test gear, take a 100k pot and rotate it until you find the resistance that makes the meter beep.

RANGES

You wouldn't use a yardstick to measure the diameter of a pinpoint, or a ruler to measure the distance across town. Inches, feet, yards and miles exist because we want to be able to measure different things using scales that make sense.

In electronics, we deal with voltage, current and resistance ranges from billionths to billions, so a multimeter has a **range switch** function that adjusts the meter's sensitivity to the range of the specific voltage, current or resistance we want to measure. Usually, the range switching function is combined with the function switch.

In a digital meter like the one on the next page, there are four digits, but the left digit can only be 1 or nothing – that's just the way they made it, it won't display any other number – so this is usually called a 3-1/2 digit meter. The highest number it can display is 1999.



What that 1999 means depends on where the range switch is set. For DC voltage:

range	max voltage
200V	199.9V
20V	19.99V
2V	1.999V
0.2V	0.1999V

When you exceed the maximum voltage, current or resistance for a particular range, the meter will either show an “E” (for error) or a “1” for the left digit, with the other digits blank. That tells you to switch to a higher range.

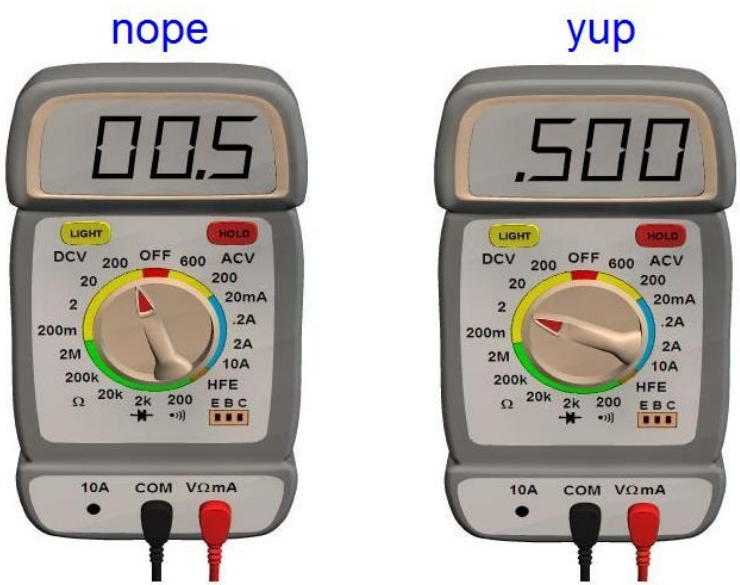
AUTORANGING

Many meters **autorange**, meaning they automatically choose the proper range for the quantity being measured. This is good and bad; good that you always get the proper reading without having to bother with the range switch, bad that you have to pay closer attention to where the decimal point is. For example, if there's supposed to be 3V on the collector of a transistor, but it's shorted and there's only 0.3V on it, you might miss the problem unless you pay attention to where the decimal point is.

ACCURACY AND RESOLUTION

If you use the 200V range to measure ½ volt, the reading you get will be “.5” which only gets you in the ballpark – the actual voltage could be 0.45V or 0.54V or anything in between. If you reset the meter to the 2V range, then you'd get a reading of “.500,” or whatever the actual voltage is, which is a lot better resolution.

Rule of thumb: use the lowest range you can, the one that best fills up the available digits.



Inexpensive digital meters are usually rated at 2% accuracy, but don't trust that. 5% error is common, with 10% error on the resistance scales. If you're going to be using a particular meter a lot, it's worth taking a precision voltage source and a precision resistor and finding out how far your meter is off, and in which direction. (Or, get a better meter. But personally, I use a cheap meter, because I'm a cheap person as my friends will tell you – and yes I do have friends, thank you very much. It works for me because I've measured all its characteristics and I know all its tricks.)

When measuring a low resistance, keep in mind that the test leads themselves have some resistance. Some meters, especially analog ones, have a “zero” knob that lets you cancel this resistance. Short the leads together and adjust the knob until the meter reads zero, then make the measurement.

Most digital meters don't have a zeroing function. You just short the leads together and note the resistance (usually around half an ohm), then subtract that from every measurement you make.

Before measuring a low resistance, it's a good idea to rotate the banana plugs in their sockets to make sure the connection is as clean as possible.

PRECAUTIONS

1. Don't greatly exceed the chosen voltage or current range. If your meter is set to the 2V range and you want to measure a 150V voltage, don't connect the leads first. Reset the range first and then connect the leads. If you're not sure what voltage you're dealing with, set the meter to the highest range. But if you don't have some idea of the voltage before you measure, you shouldn't be working on that equipment in the first place.

2. When measuring resistance or testing a diode, be sure there's no voltage in the circuit. The meter can easily be damaged when set to a resistance range.

3. Be careful when measuring current, because current flows *through* the meter and the internal shunt resistor can easily be burned out. A decent meter will have a fuse, but opening the meter to replace it is a pain, and you may not have a spare, and the fuse may have to be soldered. So just be careful.

Note that the 10A scale uses a separate banana pin connector, and there's usually no fuse. Whenever you're using the 10A scale, take a moment to double-check what you're doing before turning on the juice. The reason for the separate jack is so the range switch doesn't have to deal with that high current.

4. Get in the habit of *not* touching the bare parts of the test leads. When measuring voltages, it's dangerous – any voltage over 50VDC, 35VAC, 12V in a wet environment, poses a shock hazard. When measuring resistance, the current path through your body may throw the reading off. And chemicals deposited on the leads from your skin may create a film that will interfere with measurement.

5. Turn off the meter when not in use to avoid running the battery down. For an analog meter, this is not strictly necessary, as current is only drawn from the battery when measuring resistance. But even in that case, set the controls to a high AC voltage to minimize the chance of accidental damage.

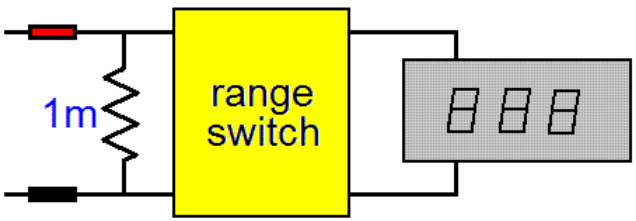
6. Be aware that attaching the meter into the circuit may upset the measurement you're trying to make. That's important enough that I want to talk about it a bit.

METER LOADING

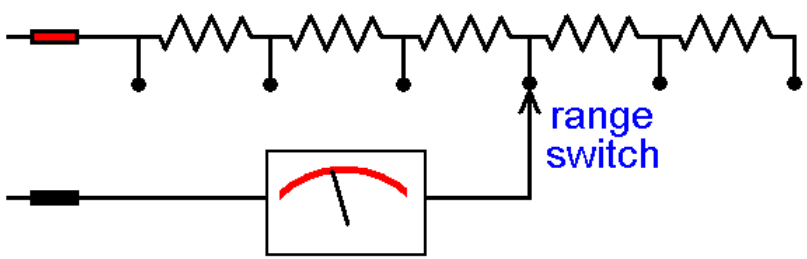
Measuring with a meter is like eavesdropping on the fight your neighbors are having. If you just stand in the doorway where they can see you, they will immediately declare a cease-fire, which is no fun at all. You have to find a lurking place where you can watch the fireworks without giving yourself away.

(If you find the unholy glee with which I said that disturbing, you're not alone. So does my shrink.)

Likewise, a meter should be designed so whatever it's attached to can hardly tell it's there. When measuring voltage, that means the meter resistance should be as high as possible, so as to load the circuit as little as possible. For a digital voltmeter, that typically means an input resistance of at least 1 megohm. Thus, when you make a measurement, a 1MΩ shunt is connected across the circuit. In a digital meter, this resistance is usually the same no matter what range the range switch is set to.

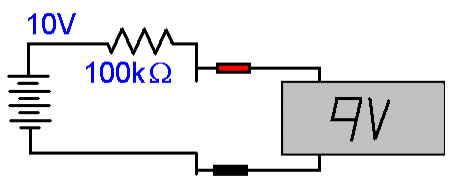


An analog (mechanical) meter is different. The meter needle must be physically moved by current drawn from the circuit. This means the meter loading resistance is usually lower than with a digital meter, and it changes when you change ranges.



An analog voltmeter is rated in “Ohms per Volt.” The “Volt” part refers to the maximum voltage of the range you're using. Say a particular meter is rated “2kΩ/V,” which is fairly common. If this meter has a 1V scale, its resistance when set to that scale will be 2kΩ. If it has a 2V scale, the resistance is 4kΩ. Changing the range switch changes the resistance: the 20V scale would have a resistance of 40kΩ and so on. This variable loading is one reason most techs prefer digital meters. On the other hand, a digital meter doesn't let you track a changing voltage nearly as well as an analog meter.

When you're measuring a fairly stiff voltage source, none of this matters. But suppose you're measuring the voltage at the end of a 100kΩ series resistor. Even a digital meter with its 1MΩ input will give you a reading that's about 10% low, because the 100kΩ series resistor and the 1MΩ shunt form a voltage divider. A beginning tech might think this indicates a problem, but the skilled tech knows this is due to meter loading. The moment you disconnect the meter, this voltage drop disappears. As time goes on, you'll get in the habit of mentally making these corrections when measuring high-resistance circuits.



You can measure a meter's resistance by setting it to one of its DC voltage scales, then connecting another meter to it, set to a resistance scale, as I showed you on page 8. Just as an example, I have three digital VOMs, and their input resistances are 1MΩ, 1.5MΩ and 3MΩ respectively.

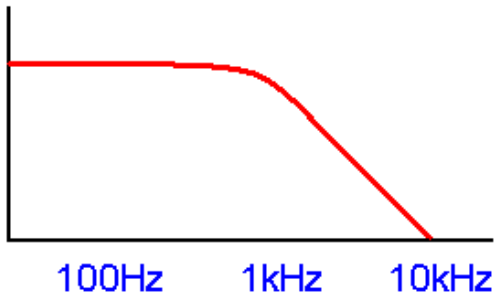
For current, the opposite is true: the meter resistance should be as low as possible, to minimize its voltage drop. If you have a circuit that's very sensitive to voltage changes, and it works differently when the meter is in the circuit, that may be the source of the problem. Remember that the test leads alone may have half an ohm of resistance.

SPECIAL PRECAUTIONS WHEN MEASURING AC VOLTAGE

The most important thing to understand about the AC voltmeter function of a VOM is that it's designed to measure AC power line voltage, which is to say, a 60Hz sinewave. If you try to to measure any other waveform, or any other frequency, you're likely to run into problems.

Frequency Limitations

An AC voltmeter's sensitivity falls off at higher frequencies. With inexpensive digital meters, “higher frequencies” may mean anything over a few hundred Hz. I have a VOM that reads 20% low at 1kHz and 50% low at 2.5kHz, and that's fairly typical, especially for cheap meters.



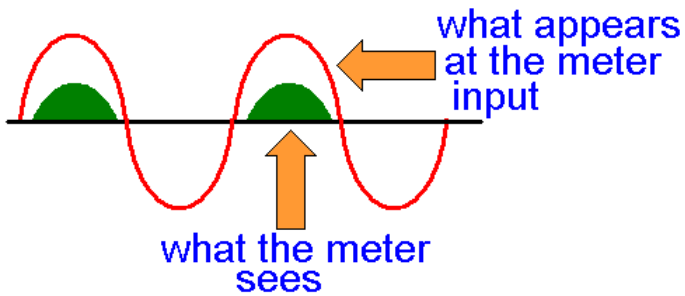
meter frequency response

It's easy to measure a meter's frequency response. Connect it to an AC voltage generator, set the generator to put out a 60Hz sine wave, then increase the frequency and watch what happens to the meter reading. A better-quality meter may be good to 10kHz, and the best meters are good to several MHz. If you're going to be measuring RF a lot, you need to own a radio-frequency voltmeter that's specially designed for the purpose.

Low AC Voltage Measurements

An AC voltmeter is a DC voltmeter with a diode in series that disconnects the meter during half of every cycle. You would expect the meter to only see half the voltage, on average, but it actually sees less than that. A diode has a forward voltage drop; that is, the voltage must rise to a certain threshold before the diode starts to conduct.

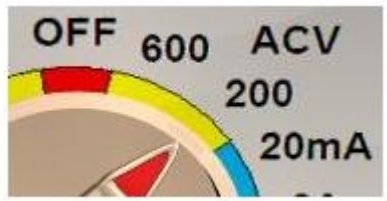
For a silicon diode, this threshold is about 0.7V. The diode in a meter is usually not silicon but some other material with a lower forward voltage drop – but there is no diode material with a threshold of zero. This means that, on a meter's lowest voltage scale, the reading will be lower than it ought to be, because the diode does not conduct for a full 50% of each cycle.



Analog meters usually deal with this problem by providing a separate scale for the lowest voltage range. The illustration shows a Simpson 260 meter. Note that the lowest range is offset from the others, and the tic marks are scrunched up toward the bottom. A tech needs to pay attention to be sure they're looking at the scale that corresponds to the right voltage range.

separate scale for low AC voltage

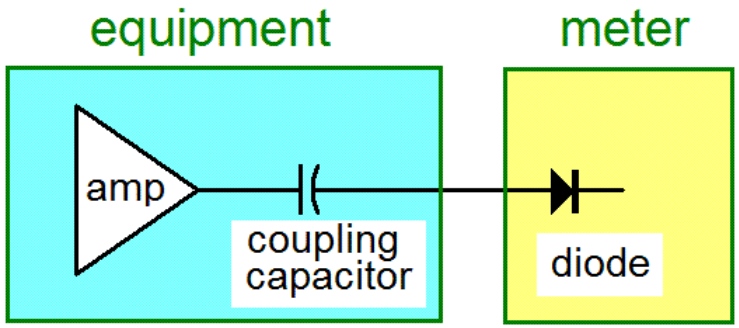
Inexpensive digital meters deal with the problem by simply not having a low voltage range. Typically, the lowest range is 200VAC. That may be fine for a tech who works with machine control systems, where the lowest voltage may be 24V.



A tech who works with lower voltages will need a meter with more sensitive AC ranges. A more expensive meter may include an amplifier and other active components to compensate for that forward voltage drop, permitting accurate AC voltage readings, in some cases, down to tiny fractions of a volt. Such meters also tend to have better high frequency response.

Capacitor Charging

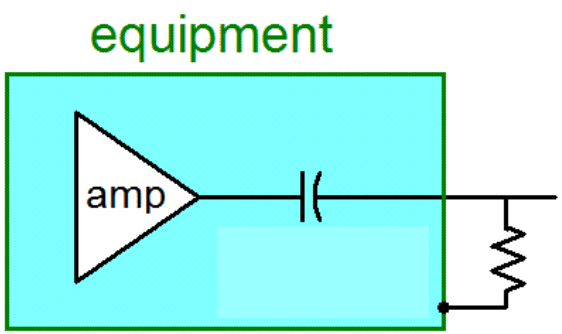
An AC meter's diode may cause another problem. In the circuit shown on the next page, an AC signal is coupled from the output of an amplifier through a series coupling / blocking capacitor. This is a very common design. Because the meter diode only conducts for part of each cycle, current only flows through the capacitor for part of each cycle, and it charges itself up.



After a while, there will be a significant negative DC voltage on the right-hand plate of the capacitor, current will not flow during any part of the cycle, and the meter will read zero no matter what the actual AC output voltage may be.

One way to tell if you're having this kind of problem is to flip the meter leads back and forth. If you get two different readings, you should assume neither reading is right.

The problem can be corrected by attaching a resistor across the amplifier output to discharge the capacitor. If the resistor is a lot lower than the meter resistance, say 10kΩ, current will flow about



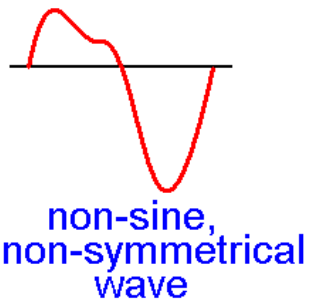
equally in both halves of each cycle, the right-hand plate of the capacitor will discharge to zero volts DC, and the meter will give a proper AC voltage reading.

Non-Sine-Waveforms

The proper way to measure an AC voltage waveform is by squaring the value at every point, averaging the squares, and then taking the square root of this average. This is called the **root-mean-square** or **RMS** measurement method. Without getting too deep into the details, the reason for doing this is so voltage, current and power measurements agree with each other. Sometimes this is called the “effective” voltage, meaning it corresponds to the wattage produced and the heat associated with that wattage.

Most meters don't measure RMS voltage, because all that squaring and square-rooting is complicated. Instead, they measure average voltage and then fudge the result. This works fine when you're measuring a sine wave, because the difference between a sine wave's RMS and average voltages is well known and all the meter manufacturer has to do is apply the right fudge factor.

It does not work when the waveform is not a sine wave, especially if the positive and negative waveform alternations are not symmetrical. To make accurate non-sinewave voltage measurements, you need a special **RMS-measuring VOM**. Not an "RMS-reading" VOM; every VOM *reads* an RMS value when dealing with sine waves, even if they're not actually *measuring* the RMS value. An RMS-measuring meter costs more, but if you really need to know the actual RMS voltage of a non-sine waveform – if, for example, you need to know if you're in danger of burning out a speaker – there is no substitute.



But with non-sinewave waveforms, RMS voltage is often not the most useful measure anyway. For example, a traditional analog video signal is usually measured from the most negative voltage peaks to the most positive voltage peaks, resulting in a peak-to-peak voltage measurement that's more useful than an RMS measurement.

For the budding tech, my recommendation is to not blow a lot of money on a deluxe meter. If you need something special later, there will be time enough to get it then. And it's just as likely that, if you need something special, it won't be a VOM at all. In the meantime, you can go ahead and measure non-sinewave signals with your non-RMS meter.

Just keep in mind that the number you get is only a very rough ballpark figure and could be off by, say, 50%, especially if the waveform is really strange. In other words, the meter gives you the order of magnitude of the signal, but nothing closer than that.

At this point in your career, you should choose a VOM based on convenience features: does it have a light-up display? Does it have a button that lets you capture and hold a reading? Does it have clips on the sides to hold the test leads? Compare features with your needs and make the choice on that basis, and resist the temptation to blow your whole bank account.

If you're going to be using the 10A scale a lot, don't buy a cheapo meter. Not because the cheapo meter can't handle 10 amps, but because the cheapo test leads can't. The direction this stuff is going, one of these days I expect to take apart a test lead and find that it's made of bubble gum wrappers. I don't know why manufacturers can't figure out a meter with a 10A scale shouldn't be paired with 2A test leads, but every cheapo meter I own is like that.

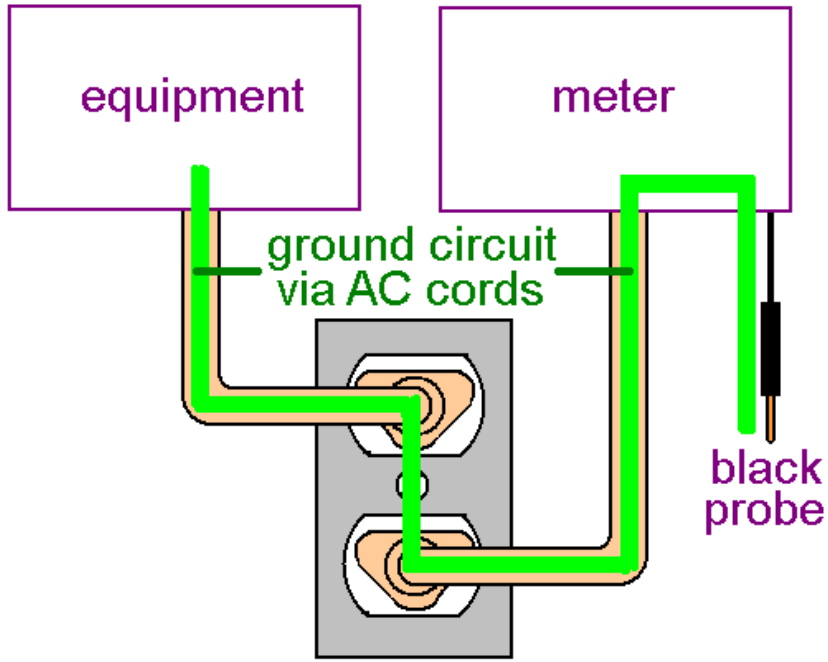
Once you have your meter, run every test on it you can think of. The highest quality meter in the world isn't as good as an average-quality meter that you know like the back of your hand.

And then get another, really cheap VOM, like a $4 special from Harbor Freight – because I guarantee you *will* misplace your main meter, or break it, or let the battery run down, and a tech without a backup VOM is like a cab driver with a flat tire and no spare.

THE BENCH VOM

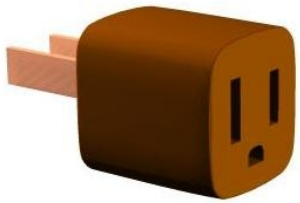
Up to this point, I have assumed there are only two connections between the VOM and whatever you're working on – the red and black test leads. A portable, battery-operated VOM has no need for more connections than that. But if you're a bench tech, you may be working with a VOM that's plugged into the AC power line. If the VOM has a 2-prong AC plug, it's fairly safe to assume its circuit is **floating**, meaning that there's no connection between the power line and the VOM circuit, so the situation is the same as with the battery VOM.

However, if the VOM has a 3-circuit power plug, that means its chassis and, usually, its black test lead are directly connected to the ground pin of the AC plug. If the equipment you're working on also has a 3-prong plug, you have an extra connection between it and the VOM, through the AC ground circuit.



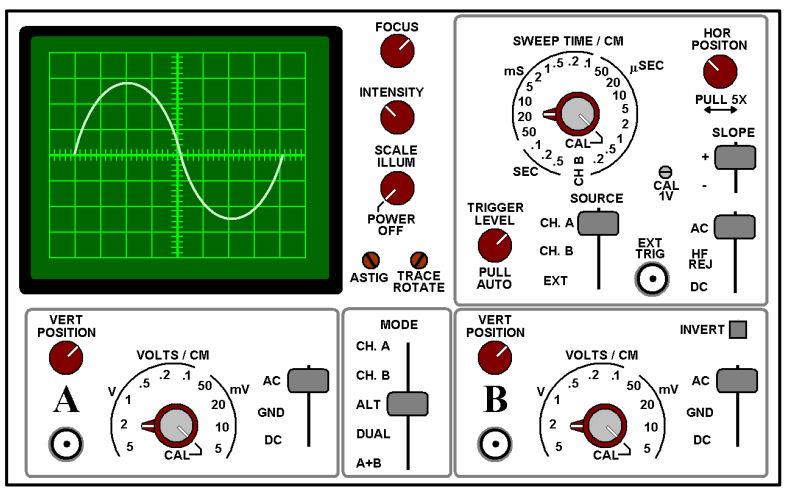
This can cause all sorts of fireworks if you're not careful. For example, if you want to measure the output voltage across a bipolar power supply, you might connect the black probe to the -DC output. But it's already connected to the ground, through the AC cords, which means you're directly shorting out the power supply. So, just be careful and keep the AC-cord ground circuit in mind.

If you run into a situation where you can't have this ground, you can use a 3-prong to 2-prong adapter to momentarily disconnect the ground pin of the equipment or the meter. Don't leave it that way, though. The rule is, if the AC plug on a piece of equipment has a ground pin, there's a safety reason for it, and you should use it.



THE OSCILLOSCOPE

The other indispensable piece of test gear is the oscilloscope, which shows actual voltage waveforms.



If you've got the EM2 study guide, it will be worth reviewing the oscilloscope discussion there. In this chapter, I'm going to present a few refinements and some tricks to keep you out of trouble.

ELECTRICAL GROUND

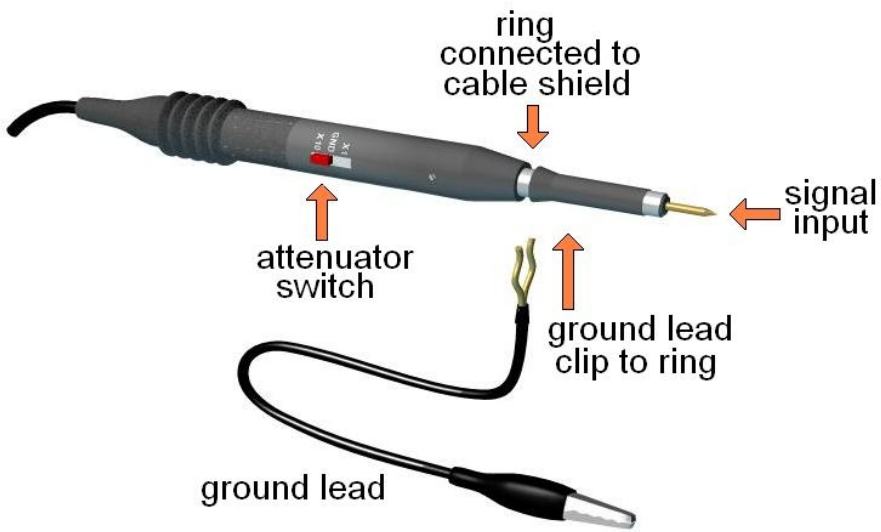
Because a scope draws more power than a VOM, it's more likely to be powered by an AC power cord instead of a battery, which means you're more likely to run into the power cord ground circuit described above. Even if the scope itself doesn't have a grounded cord, at times you may have it connected to some other piece of test gear that's grounded. Treat *all* bench test gear as if it's grounded unless you know otherwise.

A scope's signal input is almost always unbalanced, meaning there's a signal wire surrounded by a shield / ground wire, which is connected to the scope's chassis ground. Balanced inputs are very rare on general-purpose scopes, though there is a way of setting up two inputs to work in differential mode, which I will describe later.

GETTING THE SIGNAL INTO THE SCOPE

If you want a scope to display a signal, the first thing is to get the signal into the scope. That's not a slam dunk.

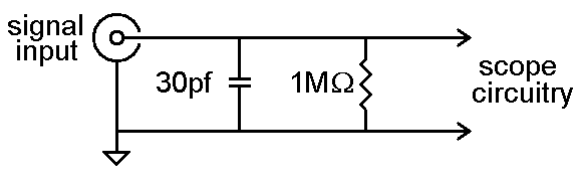
A VOM is a simple device that just measures voltage, so its probe can be a simple wire with a point on one end and a banana plug on the other. A scope, however, deals with actual waveforms, which it must display accurately, and it often deals with much higher frequencies than a VOM. Because of that, the input device, called a **probe**, is a high-technology device whose parts must work together *as a system*.



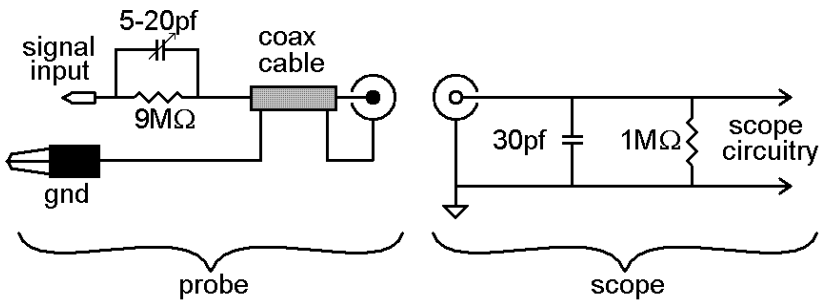
You can't chop the end off a scope probe, solder on a different probe, and expect it to work right. Even taking a complete probe from one model of scope and using it on another model is iffy. A scope is only guaranteed to work right when used with the specific make and model probes it's designed for. This is especially true of an advanced-technology scope from someone like Agilent or Tektronix.

So the first thing I'm going to tell you about using a scope is, be kind to the probes. Some techs, especially those who don't need to look too carefully at waveforms very often, buy a set of cheaper probes for everyday work and put the good ones in storage. I do that, and mine are still like new after 25 years, which is a good thing because they cost hundreds of bucks.

One thing is pretty standard: a scope's low-frequency input impedance is usually one megohm. As inputs go, that's a pretty light load. You can poke around most lower-speed circuitry without thinking too much about the scope load.



At higher frequencies, up toward 1mHz, loading gets heavier due to capacitance. The scope's own input capacitance is quite low, around 30pf, but the probe's cable has a fair amount of it.



Capacitance is like heavy grease, slowing things down. In a cable, there's no way to get rid of it. However, there's a way to make it less of a problem.

THE PROBE ATTENUATOR

A scope probe usually has a 10:1 voltage divider "attenuator" right in the probe. This knocks the signal down by a factor of ten before it ever reaches the cable. It raises the low-frequency input impedance from 1MΩ to 10MΩ, and reduces the capacitance from maybe 50pf to 5pf.

There's another benefit: with the attenuator in the circuit, it's harder for an excessively high voltage to damage the input.

And it may be necessary to use the attenuator with a high voltage anyway, because otherwise the waveform may too large for the scope to display, even with the range switch set to the least sensitive position.

Some probes are made with attenuators permanently wired in. Most have a switch with three positions:

- 1X – attenuator out, the signal goes straight through.
- 10X – attenuator in, the signal gets knocked down by 10:1.
- GND – the signal input is connected to ground (shield). This does not connect the input pin to ground; that is, it does not short the input. Rather, it disconnects the input pin completely, and shorts the signal wire to ground inside the probe.

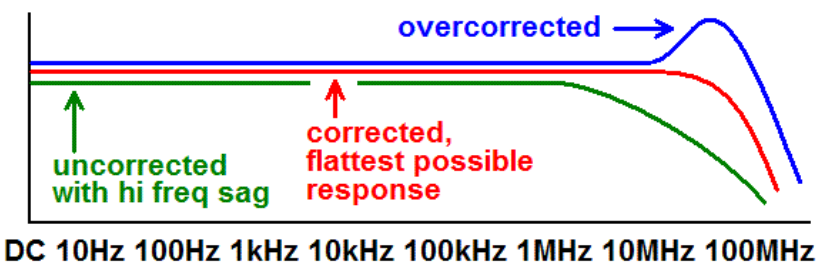
When using the 10X probe, you have to shift gears mentally, because the range switch settings are all 10X off. For example, if you want the scope to show 1 volt per centimeter, you have to set the range switch to 0.1V per centimeter. That's a ten times increase in sensitivity, which cancels the ten times reduction in sensitivity from the probe attenuator.

Many techs get in the habit of leaving the 10X attenuator in the circuit all the time, except when they need maximum sensitivity to look at a weak signal.

PROBE CALIBRATION

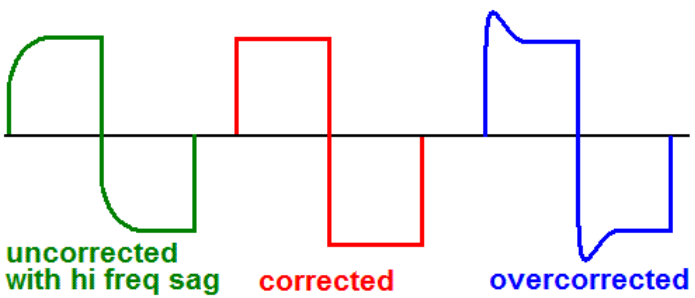
You want the scope to respond to all frequencies equally, e.g. a 1V sine wave should look like 1V whether it's 10Hz, 10kHz or 10Mhz. The scope maker has already made it as flat as it can be over its intended range. However, you have to tweak the probe.

A scope probe tends to “roll off” high frequencies, that is, attenuate them, with greater attenuation at higher frequencies. Inside the probe, there's a variable capacitor that's used to correct that. You stick a small screwdriver in the side of the probe and tweak the capacitor until the response is flat from DC all the way up to the highest frequencies the scope is designed to display.

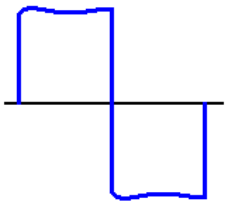


The “long way” of adjusting the frequency response would be to take a sine wave generator and run the frequency up and down until you've got the probe adjusted. However, there's a much simpler way. As any musician would tell you, few tones are “pure.” Usually, a musical tone contains energy at the fundamental pitch, the basic pitch of the note (e.g. Middle C), plus “overtones” that make the tone more musical and give it a characteristic sound. Scientists know about overtones too, though they call them “harmonics.”

It happens that a **square wave** with sharp corners contains harmonic energy all up and down the frequency spectrum. If the probe upsets the frequency balance, it will also upset the wave shape. So all you have to do is feed a square wave into the probe and tweak it until it looks nice and square on the scope face. And, scope designers being the helpful people they are, a scope will usually have a terminal on the front with a square wave signal on it.



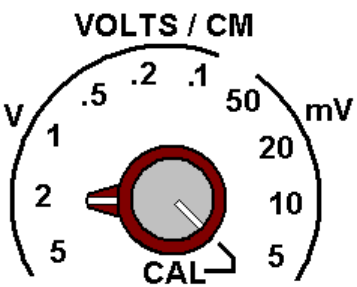
The illustration to the right shows what can happen when you're not using the right probe. No matter how you tweak it, you can't get all parts of the square wave to look right. That means you can't trust the size of the waveform on the scope screen to correspond to the actual voltage. You can still use the scope to look at waveforms, but not to measure them, except at low frequencies.



Digital scopes need their probes calibrated just like analog ones, but some of the better scopes are able to do that in software.

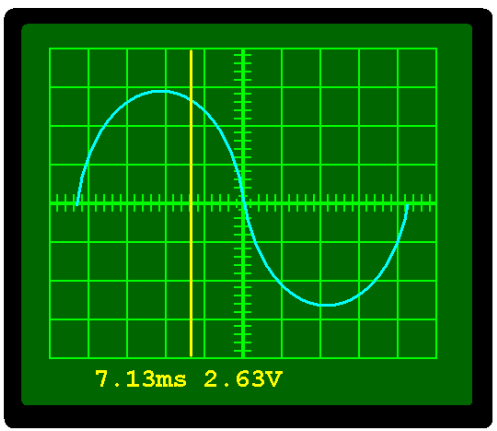
The probe shouldn't work any different on 10X than 1X, other than loading the circuit more lightly, but check to make sure. By now you'll know to say it before I do: "Know your equipment."

THE RANGE SWITCH



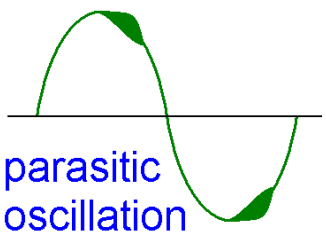
I won't have to say much about the range switch because it works the same way as the range switch on a VOM. You rotate it until the waveform pretty much fills up the screen. Note that, along with the switch, there's a "fine adjust" pot. This can be used to adjust the size of the waveform, but calibration is lost in the process. If you want to measure parts of the waveform by counting squares on the screen, there has to be some relationship between the input sensitivity and the square size.

If you look at the fine adjust pot, you'll see that there's a calibration mark at one end, usually clockwise. When you set the pot all the way to that end, the range switch voltage increments are what they say they are. Some scopes even have a little light to remind you when the pot is not in its "calibrated" position.



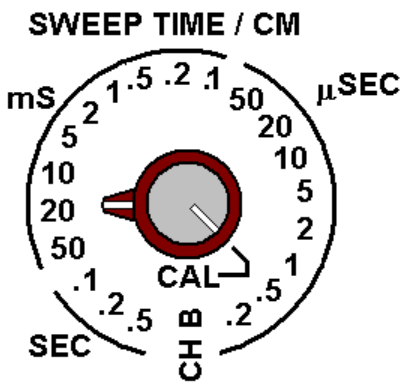
A modern digital scope usually does this a different way. It will have a **cursor** which you can move back and forth across the waveform (yellow in the illustration at right). Wherever you put it, not just at the peak, it will tell you what the voltage is at that point in the wave. But you have to actually look at the wave to be sure the number makes sense. Sometimes, with a strange waveform, the cursor reading goes haywire.

For example, there's a thing called **parasitics**, where the circuit becomes unstable and goes into high-frequency oscillation over part of the waveform. The scope's internal circuit will have trouble measuring that. But a little common sense here: this is a malfunction. You shouldn't be measuring it, you should be fixing it, or at least flagging it for a senior tech to look at.



THE SWEEP SWITCH

In an analog scope, an electron beam **sweeps** across the screen from left to right at a constant rate, laying out the signal waveform as it goes. A digital scope performs the same function, with some extra memory-reading-and-writing thrown in. How much space a wave takes up on the scope screen depends how fast the beam sweeps across. The faster it sweeps, the more it spreads out the wave and the better you can see it. On the other hand, the faster it sweeps, the sooner it's over, so the less time you get to look at. You have to choose.



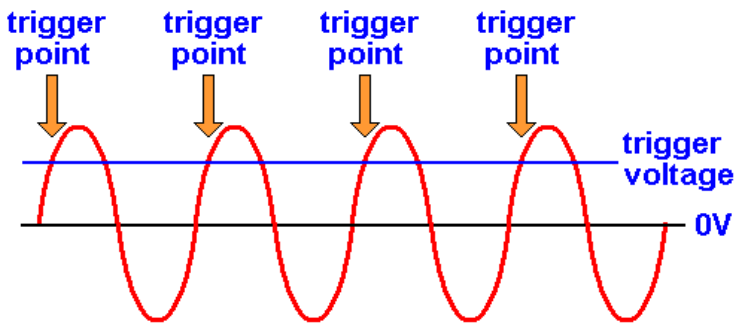
REPEATING SWEEP

Things get a lot easier if you're looking at a waveform that repeats continuously, because then you can sweep again and again and look at it for as long as you care to. Fortunately, many signals are like that. You can look at the signal for a while with a fast sweep, to study the waveform closely. And then you can look it for a while with a slow sweep, to be sure it really is repeating exactly the same, with no occasional hiccups.

THE TRIGGER

To keep the waveform steady on the oscilloscope display, each sweep has to start at the same point in the signal waveform. One way you can do that is to carefully adjust the sweep pot until the sweep generator is running exactly the same frequency as the input signal. Two problems with that. One, it's a pain in the pooter. Two, when you're dealing with high frequencies (e.g. 1MHz), it's almost impossible to adjust the two frequencies precisely enough to give you a stable display. So we let an automatic **trigger** circuit inside the scope handle it.

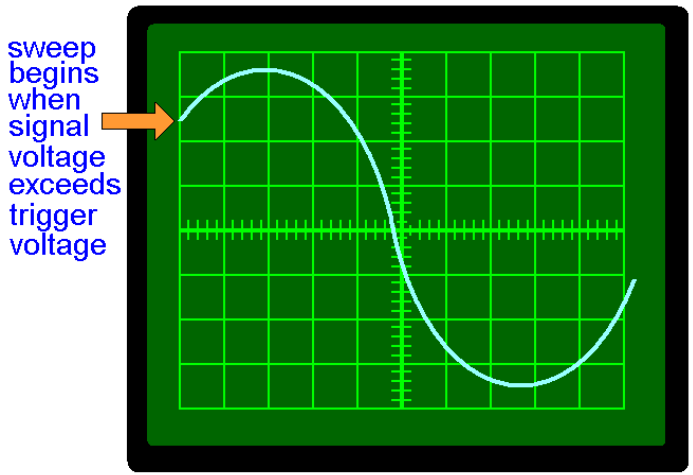
Think of the gate that releases a race horse. The trigger holds back the sweep until the signal waveform gets to a chosen voltage. If the waveform is always the same, and the trigger voltage is always the same, then the sweep will always begin at the same point in the wave. The electron beam will keep drawing the same waveform on top of itself, and you'll see a stable display.



The obvious place to set the trigger voltage is zero, or more specifically, the positive-going zero, the point where the waveform crosses the X-axis going from negative to positive. After all, that's where the wave “officially” starts. Lots of techs set the trigger at that point.

But sometimes there's something happening right at the zero-crossing that you want to look at, meaning you want the displayed waveform to start at some other point. On an analog scope, there's a knob to let you set the trigger point where you want. A digital scope does the same thing, though usually with pushbuttons, and with nice cursors that tell you exactly what trigger voltage you've selected.

In the illustration to the left, the trigger has been set to a voltage well above zero. The resulting display would look like the illustration below.



THE SINGLE SWEEP

Unfortunately, not every waveform repeats. In this case, you'll have to get good at setting up the trigger circuit as a **one-shot** to trap a single event. For looking at single events, a digital scope is the only way to go. Digital scopes quantize waveforms and put them into memory as part of their normal operation. It's easy for them to sift through their files to find a particular event, and hold it up in front of you for as long as you want to look at it.

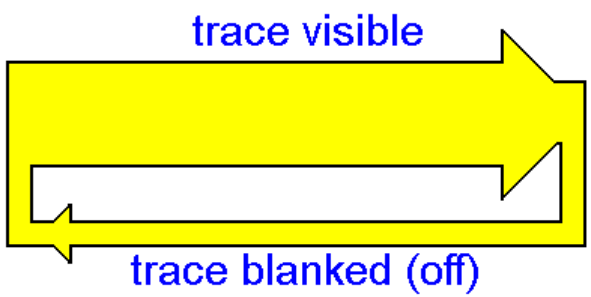
NOT SEEING EVERYTYING

So now you know how to use a scope. You knew it by the time you were done with EM2. What can I give you in EM5 to boost you to the next level of expertise, so those other wretches who haven't known the magnificence of these study guides will cower at your feet?

How 'bout this: scopes miss things. Especially things that only happen once in a while. Like, the occasional glitches that are the whole reason a piece of equipment needs to be fixed in the first place. Oh, joy.

Blindness During Retrace

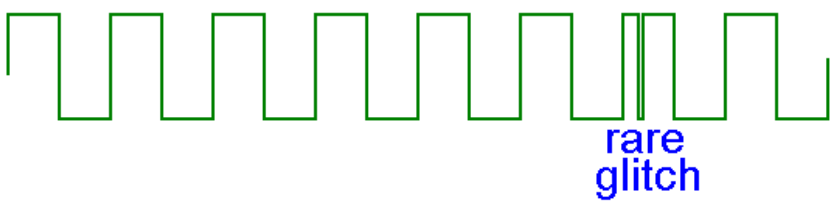
First off, in an analog scope the electron beam isn't scanning left to right all the time. For a very short time at the end of each trace, it's moving right to left to get ready for the next trace. This is called the **retrace** interval, and during the retrace, the beam is shut off – the scope is blind. What if something happens just then?



Blindness During Trigger Hold-Off

You can keep this from being a problem by setting the sweep rate so the display shows just a little more than one signal cycle. But then, when the beam moves back to the left, the trigger will hold it off for the rest of that second cycle, and only trigger on the third. What if something strange is happening every other cycle? Oscillators, for example, sometimes have a habit of tossing in a glitch every other cycle when they're not working quite right. (As any tech will tell you, it's a lot harder to fix something that's 10% broken than 100% broken.)

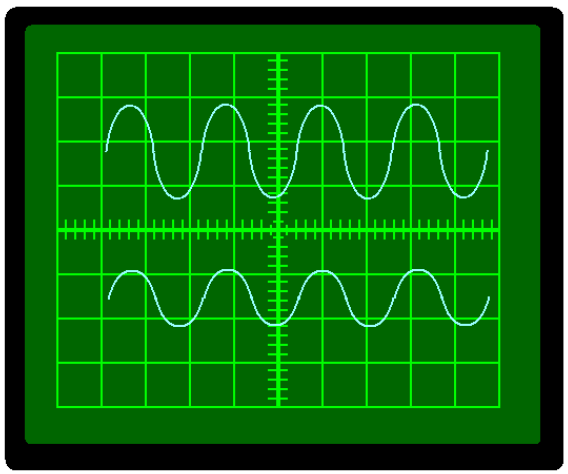
This also happens with digital scopes. The triggering works differently, but the result is the same: the screen doesn't show what's happening at every moment. The best way to catch this problem is to slow down the sweep and look at a lot of cycles in a row. You may have to look closely, because a glitch that only occurs once in a while isn't going to be very bright. If you're very lucky, you'll work with a digital scope that displays unusual events in a different color.



Blindness During Alternate Sweep

This is an analog-scope problem that is going away as analog scopes are being replaced by digital.

Most general-purpose scopes are **dual trace**, meaning they can show two waveforms at once. The vertical sensitivity is separately adjustable for each.



The sweep frequency is *not* separately adjustable; the whole idea is to compare two waves that are happening at the same time – for example, the waveforms at the input and the output of an amplifier.

But the waves aren't really happening at the same time. With few exceptions, an analog scope almost always has just one electron beam. So, what happens is the single beam **alternates**, showing first one wave, then the other. If the waves are all the same, the fact that every other one is being skipped shouldn't make any difference. But if they aren't...

Here's a quick trick. When your scope is showing two traces, the trigger will be timed to one trace or the other, depending on where you have the switch set. Momentarily disconnect that input, then connect it again. What you're doing is disturbing the sync triggering. Every time you put it back, the display should look like it did before. If it changes, look to see if there isn't part of the wave that isn't being displayed every time.

With a very slow sweep, the back-and-forth switching makes it hard to read. A n analog scope also provides a **chopped** switch setting, where the beam goes back and forth between the waves, too fast to see. Use the alternating setting for signals of, say, 1kHz or higher (depending on the scope) and the chopped setting for frequencies below 1kHz.

And a rule of thumb: don't have two traces on your scope screen, except when you need them.

Digital scopes have fewer of these problems, but there are other problems that analog scopes don't have. When you're having trouble finding a problem, speed up and slow down the sweep to see if that reveals something new.

Scope Changes Circuit Behavior

Sometimes, when a unit is occasionally misbehaving, connecting the scope will fix it. Or, it may make things worse. What's usually happening is that a digital transition, a sharp wavefront, is coupling from its origin point in the unit to somewhere else in the unit where it's not supposed to be. When the scope probe is added to the circuit, its capacitance changes the wavefront.

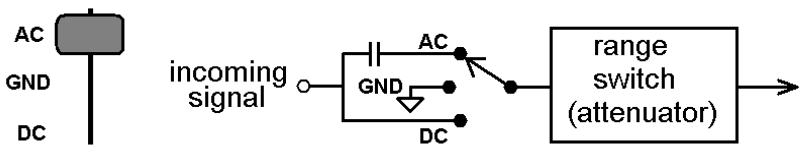
Poke the probe around in the circuit, right in that immediate area, until you find the point it affects the most. Look at the schematic diagram to see if you can figure out what's drifted outside normal limits.

Don't forget to try putting the probe on the DC power supply rail. Glitches sneak from one place to another via DC rails all the time. If putting the probe on the rail changes behavior (or if the scope shows you voltage spikes on the rail), the DC filter capacitors have probably gotten weak and need to be replaced.

That can be expanded into a general rule of thumb: in old equipment, capacitors are always suspect. They're especially suspect if they've lived their whole lives next to something hot. They're most suspect if they're electrolytics. In audio gear, If the unit works sorta okay but there's a lot of hum, the problem is probably dried-out electrolytic power supply filter capacitors. They just do that.

AC & DC INPUTS

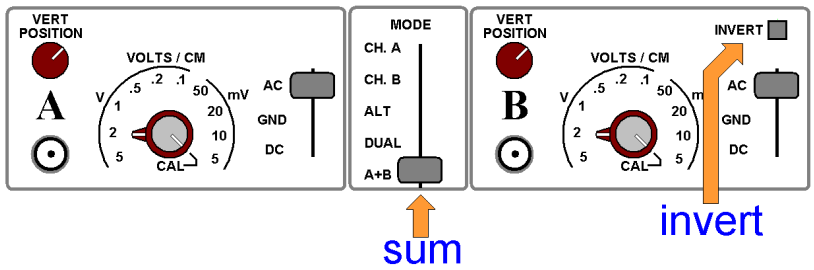
Often, you will want to look at a small AC signal at some point in a circuit where there's also a large DC voltage. The scope will have a switch that allows you to remove the DC component by putting a capacitor in series with the input.



The main caution here is to remember which position the switch is in, so you know what the image on the display really represents. If a voltage is varying slowly, it will not be displayed. (The low-pass transition frequency is usually a few Hz.)

DIFFERENTIAL INPUTS

Most scopes are provided with an “A minus B” setting, or a switch that inverts the polarity of one of the inputs. In the example on the next page, the MODE switch is set to A+B, which would normally result in a single trace that's the sum of the voltages at inputs A and B. Then the INVERT button is pushed, flipping the polarity of input B.



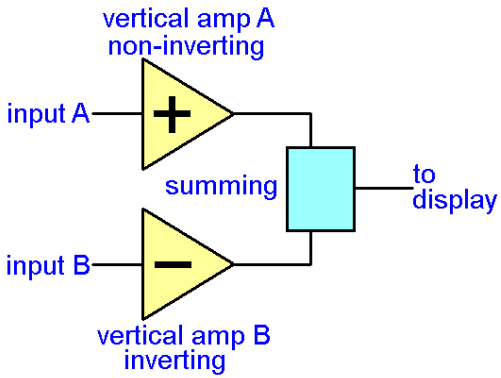
The result is an A-B function; that is, a single trace that shows the difference between the voltages at inputs A and B. This can be used as a differential (balanced) input. But you have to do it carefully.

First, the range switches need to be the same on both inputs, and the range pots need to be in their “calibrated” position.

Second, both inputs must be switched to either DC or AC, not one of each.

Third, the probe switches must both be at 1X or 10X, not one of each.

Fourth, if you're trying to look at a small part of a large voltage, you may be in trouble. This isn't really a balanced input, it's two unbalanced inputs feeding two unbalanced amplifiers, which separately amplify the signals at their inputs. Only after this amplification is done do the inverted and non-inverted signals combine, giving you a differential display. If either of the amps is overdriven, the display will go haywire.

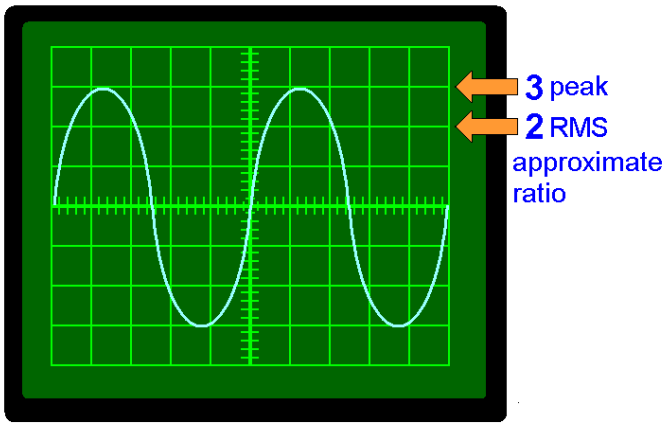


My practice is to connect one input to one side of the voltage and adjust it for a good display. Next, I connect the other side and adjust it so the voltage is canceled. Then I start turning up the range switches until I can see the small difference voltage I'm looking for. If everything suddenly goes crazy, I know one of the vertical amps is clipping, and I've reached the limit of how much I can amplify the difference voltage. If that's not enough, too bad. I'll have to build a little differential amp or something.

PEAK / RMS VOLTAGE

It's easy to find the peak voltage of a sine waveform on a scope – hey, it's that hump on top, duh – but so not easy to estimate the RMS voltage. Here's a quick and dirty: it's a ratio of 2:3

Well, no it's not really. The RMS voltage of a sine wave is the square root of ½ the peak voltage, which is 70.7%. A 2:3 ratio is about 67%. But you know what? That's only a 6% error. So, let's say you've got the scope set to 5V per division and you want to adjust a sine wave to 10VRMS. If a rough guess is close enough, set the waveform so the peaks are 3 divisions high, 15V.



And if a rough guess isn't good enough, you're going to have to make a precision measurement with a precision meter. Or, if you're lucky, you'll be using a nice new digital scope with functions like that built in.

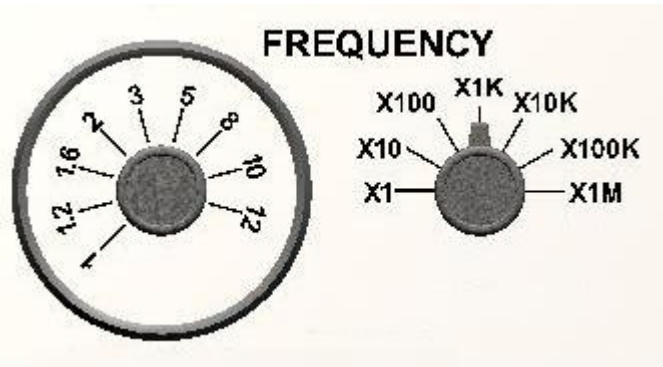
THE FUNCTION GENERATOR

The third essential piece of equipment is a **generator** that makes signals for the VOM and scope to look at. The most flexible type, the one you'll see in nearly every basic workbench setup, is the **function generator**. The signal output is measured in volts. A function generator is designed to work into a wide range of loads, from 600Ω (sometimes 50Ω) up to infinity (open circuit, no load).

I gave a very brief description in the EM2 study guide, but now it's time to take a closer look. We'll start by looking at each of the controls. The two most fundamental aspects of any repeating waveform are **frequency** and **amplitude** – how often the waveform repeats, and how big it is.

Frequency Control

The **frequency control** is most often a simple knob. The knob is usually attached to a potentiometer. The rotational range of a pot is usually about 300^{O}, and the generator is designed so turning the frequency knob from one extreme to the other will cause the frequency to vary over a bit more than a 10:1 range, e.g. from 1Hz to 12Hz. On most generators, the number scale is simply printed on the knob.



One of the nice things about function generators is that they can cover a very wide range of frequencies. Even a cheap one can usually do 1Hz to 1MHz, a 1,000:1 range. If the frequency control knob only covers a 10:1 range, this means we also need to have a frequency **range switch**. This is a **decade** switch, meaning it switches in steps of 1, 100, 100, 1,000 and so on. This means one number scale works for all ranges.

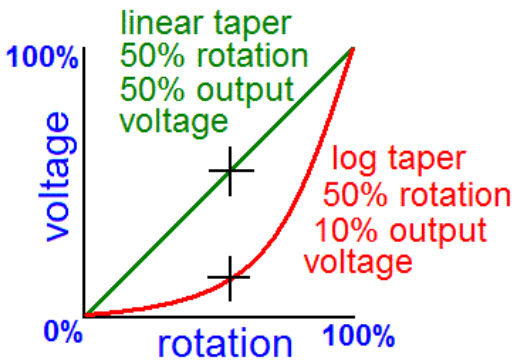
The switch and the pot are used together to set the output frequency. Making the pot cover a bit more than a 10:1 range insures that there is no frequency that cannot be generated.

Some generators have a **vernier** knob which permits extra-fine adjustment of frequency. Keep in mind that the frequency is only as precise as the numbers on the scale. On a cheap generator, they may simply be silk screened onto the knob, crude at best. In any case, the way to set the generator most accurately is to connect a frequency counter to the output to actually count the number of cycles per second.

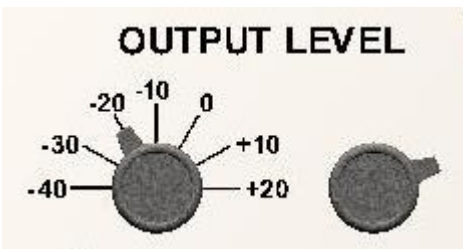
Level Control

The **level** or **amplitude control** is usually a potentiometer voltage divider followed by an output amplifier. This may be a **linear taper** pot, in which case the output voltage is just proportional to the position of the pot.

However, this isn't ideal if you want to be able to set the output to a wide range of output voltages, which you do. Trust me. A better generator will have a **log taper** pot, in which setting the pot halfway up doesn't give you half the maximum voltage, but $^1/_{10}$ the maximum voltage. With a log taper pot, you can set the output to any level over a 100:1 range without too much trouble.



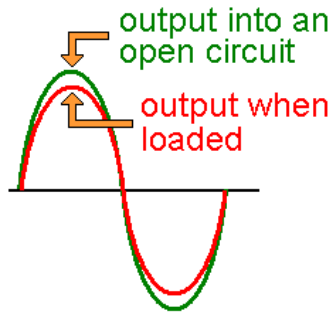
In use, the behavior of a linear pot is that the level doesn't seem to change much over most of its rotation, but attenuates suddenly to zero near the pot's counterclockwise limit. This makes it difficult to set the generator to a low signal level. Even top-quality generators sometimes have this problem; you'd think they would know better.

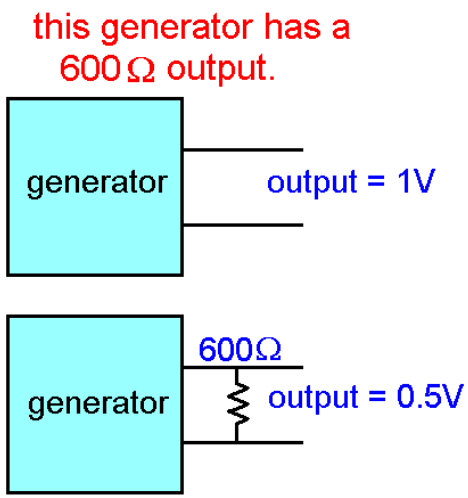


The level control, like the frequency control, may include a range switch. This lets you set the output to any voltage over a very large range, say 0.1mV to 10V.

Level vs. Loading

Few signal generators have a "stiff," very-low impedance output. This means the voltage will drop significantly if the output is loaded. This may not be important, as you can simply adjust the output level to compensate. Even so, I run into lots of cases where I have to think about the generator's impedance.



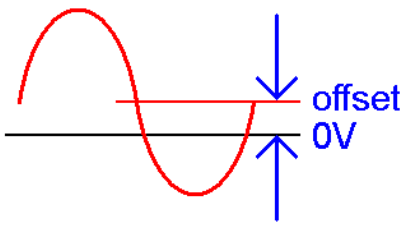


Most of the generators I've used have had either a 50Ω output or a 600Ω output. You can tell which by connecting a 50Ω or 600Ω resistor across the output; whichever one causes the signal voltage to drop by 50% is the generator's output impedance. What's going on, of course, is that the generator's 600Ω and the external 600Ω make a 2:1 voltage divider.

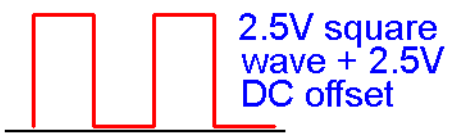
Almost all function generator outputs are unbalanced; that is, there's a signal connection and a ground connection. The connector is usually either a BNC jack or binding posts.

DC Offset Control

When you turn the output all the way down, you expect the output voltage to be zero. When you turn it up, you expect it to be an AC voltage centered on zero volts. But many function generators have a **DC control** that allows you to change the DC voltage of the center-line of the AC waveform. In other words, you can create an output that's a combination of AC and DC, or if you like to think of it this way, an AC signal with a DC offset plus or minus.



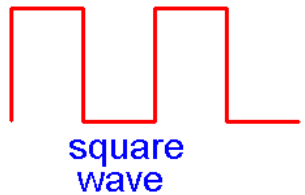
One thing that's useful for is creating a 0V / 5V square wave for testing digital circuits when you don't have an actual digital tester available.



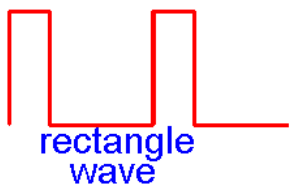
Waveform Control

The thing that sets a function generator apart from most other generators is that you get to choose which waveform comes out. A typical generator has four output waveforms:

SQUARE WAVE: a wave that alternates plus and minus, spending an equal amount of time in each state. This is called a 50% **duty cycle**.

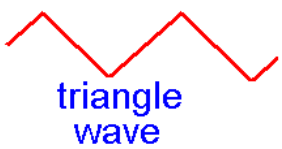


Some generators permit you to change the duty cycle so one alternation is longer than the other. This is called a **rectangular wave**. If you set the duty cycle so it's extremely unequal, you get a **pulse generator**.



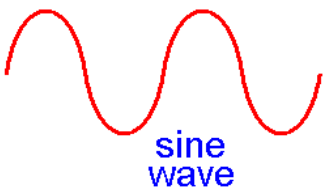
The positive- and negative-going edges of the wave, the **rise** and **fall**, are extremely fast. This, and the wave's squared-off shape, make it a good test signal for uncovering instability, ringing, high-frequency rolloff and time smearing in a system.

TRIANGLE WAVE: a wave that **ramps** up and down smoothly. The nice thing about a triangle wave is that the slopes are straight lines, so if a piece of equipment distorts the waveform, you'll see it.



SAWTOOTH WAVE: essentially a triangle wave where either the rise or the fall has been made very fast, ideally instantaneous. A difficult wave for a system to handle without screwing up, meaning it makes a revealing test.

SINE WAVE: a smoothly varying waveshape that, ideally, represents **simple harmonic motion**. It's the Y-axis component of the motion of a smoothly turning wheel.



The sine wave's significance is that it's the only pure waveform, the only one that does not contain any energy at any frequency except the fundamental waveform frequency. a 1kHz sawtooth wave contains energy at 1kHz, 2kHz, 3kHz, and every multiple of 1kHz all the way up the frequency spectrum. These are called **harmonics**. On the other hand, a 1kHz sine wave only has energy at 1kHz – *if* it's really a perfect sine wave.

The sine wave is the function generator's stumbling block. It's the waveform naturally created by a resonant tuned circuit, but a function generator doesn't have resonant circuits. It fakes a sine wave by taking a triangle wave and squashing the peaks. It's hard to reduce the higher harmonic content to less than 1% of the total energy, and that 1% is concentrated at the positive and negative peaks, so it's really worse than the percentage would suggest.

Most of the time, a few percent distortion won't matter. But when you need a pure sine wave – which is fairly often – the function generator is simply the wrong tool. I'll mention a couple of alternatives at the end.

Modulation Inputs

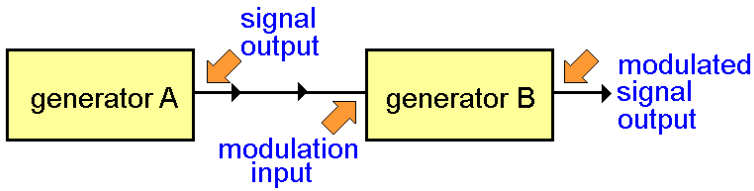
We naturally think of a waveform generator as something that keeps cranking out the same waveshape at the same frequency and amplitude, but it's often nice to be able to vary it. Of course, you can do that by twisting the knobs, but lots of times you want to do it electrically – you want to use an externally provided signal to vary the function generator's signal in some way. This is called **modulation**.

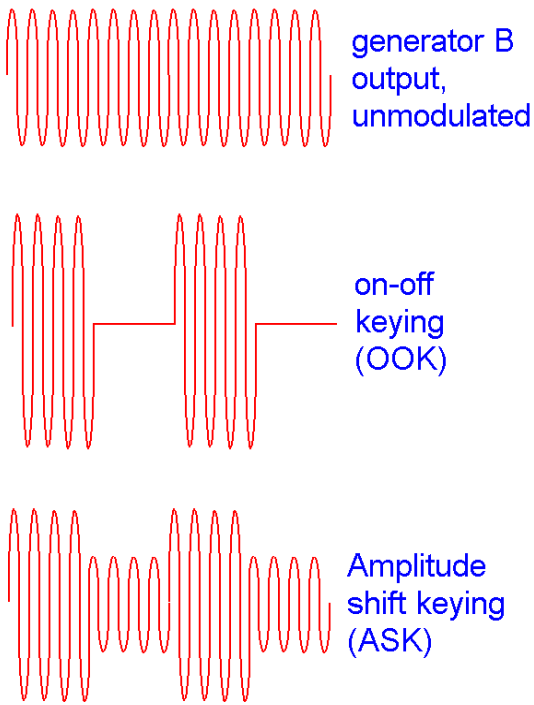
Modulation is the way information is transferred over the air, as in AM, FM, TV, etc etc etc. You start with a high-frequency **carrier** signal, and then use a lower-frequency **information** or **data** signal to impose variations on it. At the receiving end, these variations are detected and the information is recovered.

One of the best features of function generators (most of them, anyway) is that they let you modulate the signals they're putting out. There's a jack to feed a modulating signal into, and usually a knob to let you adjust the amount of modulation. You can usually choose AM or FM.

AM

AM stands for **amplitude modulation**. "Amplitude" is, of course, just a brainy-sounding word for "amount," which in this case means amount of voltage. You set the generator's signal output voltage in the normal way, then the modulating signal imposes amplitude variations on it. When the modulating signal is speech and music, we get AM radio. But we can also use one function generator to modulate another one, and that can have a lot of uses. For example, we can mimic a transmitter, which gives us a signal we can control for testing a receiver.



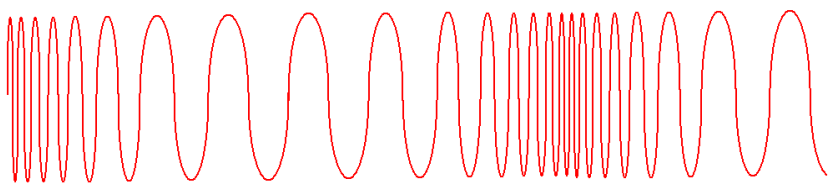


Example: if the signal from generator A is a square wave, and you turn the modulation knob on generator B way up, it will completely shut generator B's signal off part of the time. This is equivalent to the radiotelegraph signals, i.e. Morse Code, of a century ago. The generic name for this is **on-off keying**, abbreviated **OOK**.

Digitally-generated OOK patterns are used in car door openers, TV remote controls, radio-controlled model airplanes etc. A smaller amount of modulation results in **amplitude-shift** keying, or ASK. It's easier to do some things if the generator's output never completely disappears.

FM

FM stands for **frequency modulation**, in which the generator's output voltage stays the same, but its frequency shifts up and down in response to the modulating signal.



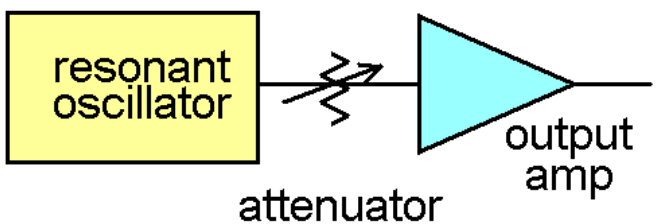
Here's one thing you can do with it: set the modulating generator to put out a low-frequency sawtooth wave. Feed it into the second generator, set the second generator's output to sine wave, and you'll get a sine wave whose frequency repeatedly **sweeps** over a specified frequency range. One of the things this is useful for is testing the frequency response of a system.

I could write a whole chapter on ways to use the modulation functions, but that really has more to do with RF and wireless, which is EM6. If you wind up using function generators in your job, you will be surprised at the number of things they can do.

Before I end this chapter, a brief look at two other ways of generating waveforms.

THE RESONANT GENERATOR

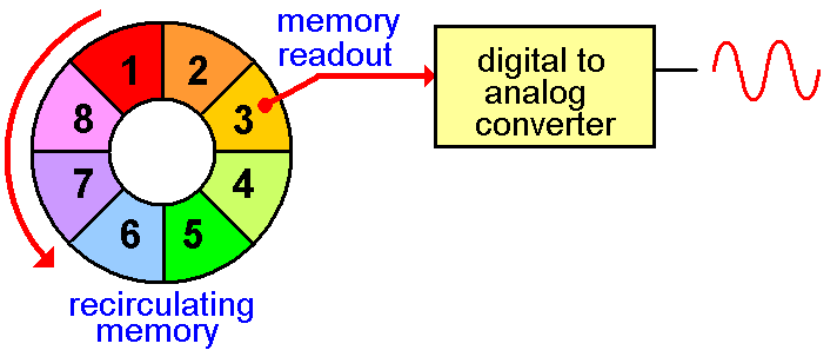
There are many times when the function generator's crude sine wave is just not pure enough. A piece of equipment often has to be able to pass a signal with essentially no distortion, and there's no way you can tell if it's doing that if the test signal itself is distorted. **Sine wave generators** use a resonant circuit that generates a very pure sine wave naturally. As the name implies, a sine wave is the only kind it can generate; it won't make a square, triangle or sawtooth wave.



THE DIGITAL GENERATOR

Because the traditional wine wave generator's frequency is determined by a resonant circuit, it's difficult to frequency-modulate or sweep a resonant generator. But nowadays there's a way to use digital circuitry to build an analog sine wave, which gives us the best of both worlds: a pure sine waveform along with easy AM and FM capability. And, in the bargain, very precise frequency control.

The digital generator starts with a bunch of digital numbers called **samples** in its memory that represent the voltage at various points on the sine wave. A clock circuit simply scans these numbers out, one after another, over and over, and a digital-to-analog converter changes the digital numbers to voltages.



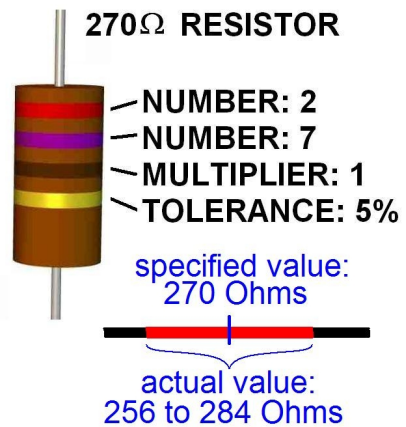
How clean the waveform is depends on how many samples there are and how precise each sample is, and we get to choose those, so we can make a very clean sine wave.

THE ARBITRARY WAVEFORM GENERATOR

Of course, there's no need to limit ourselves to sine waves. Memory is so cheap these days, the generator can store triangle wave samples, sawtooth wave samples, or whatever. In fact, we can load the memory with any kind of arbitrary waveform we want. This is cool because we can create a custom waveform to mimic any real-world situation. Some equipment manufacturers even have testing waveforms that you can download into an arbitrary waveform generator, specially made to test their equipment.

ACCURACY, TOLERANCE, RESOLUTION

Unfortunately, no measurement is ever exact, just as no resistor value or anything else is exact. A tech will avoid a lot of trouble by adopting the mindset of, “how close are we?” and “How close do we need to be?” In other words, when you think “270Ω resistor” you should get a mental image of a number line spanning 256Ω to 284Ω (for a 5% resistor).



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This sloppiness runs all through reality. We live in an analog world, a world of greater and lesser amounts. You can count tree branches as if they were all the same size, but they're not, and branches smaller than some arbitrary size fall out of the category of “branches” and into the category of “twigs.” We ran into the same thing in EM4, when we looked at binary voltages, and where various logic chips draw the line between “0” and “1.”

Keep in mind these three factors:

- Accuracy: how close an actual number is to the number it's supposed to be. Component values are not perfectly accurate, nor are instrument measurements.
- Tolerance: the range over which an actual number may vary, from lower-than-specified to higher-than-specified.
- Resolution: how finely something can be measured. For a digital voltmeter, for example, the resolution is ½ the significance of the right-hand digit. For a 3½ digit voltmeter set to the 2V scale, resolution is plus or minus 0.5mV. Any voltage within a 1mV range will show up as the same number on the display.

WRAPPING UP

If you started with the EM1 study guide and worked through all of them in sequence, this is the end of the technical part of the EM5 series. There's just one chapter left, which deals with non-technical topics. Then you'll be off to further studies with more advanced instructional material, or to an entry-level technician position, or both.

If you have been taking the EM exams and earning the EM certs, once you finish this fifth EM you'll also qualify for the CETa, the Certified Electronic Technican, Associate level. That is the prerequisite you'll need if you want to go on to earn journeyman ETA certifications.

There is one big hole in the EM5 series: We haven't said much about RF and wireless stuff. ETA has added an EM6 cert, which is optional (not required for a CETa, though maybe it should be), covering wireless applications. As this is written, I haven't got a study guide for EM6. But there are a number of other resources available, including an RF introduction by ETA officer Ira Wiesenfeld. You can download the list of competencies from the ETA website, and as with all ETA certs, the list includes recommended reading.

End of chapter 9

EM5 Chapter 10
WORK PRACTICES

Objectives of this chapter:

- *Dealing with the workplace as an effective employee*
- *Dealing with the boss*
- *Dealing with the customer*
- *Dealing with fellow employees*
- *Calculating productivity*
- *Recordkeeping*
- *Work space organization*
- *Diagnosing and repairing an equipment malfunction*
- *Obtaining service literature*

This chapter continues the discussion of non-technical issues that we started in chapter 12 of the EM1 study guide. Not all students go through these in sequence, so I'm going to be copying stuff from EM1 and pasting it here. If you've done EM1, a lot of this will be familiar. I'll put the cloned stuff in green, so you can skip over it if you want to, but it won't hurt you to read it twice. There is no practice exam, because we're not dealing with data but with personal habits.

Half of being a successful tech is knowing how to work with electronics. The other half is knowing how to deal with the workplace, customers and co-workers. As I said in EM1:

"What a shame it is when a person spends a lot of time and a small fortune learning about electronics, and then can't hold a job because they can't get along with co-workers, can't deal with the public, can't or won't keep records, don't show up on time, dress like a slob etc."

BUSINESS AND PROFITS

Having started by quoting from EM1, I might as well continue. The first problem a lot of newly certified techs run into is that they've been taught that business and profits are evil, and now here they are working for a business and trying to help it make a profit. How do you handle that? Here's how I handled it in EM1:

"The first thing you have to do is come to terms with a basic fact: the purpose of a business is to make a profit. If you're one of the millions of people who think business is inherently evil and "profit" is a dirty word, this is going to be a problem. But I have to ask you: where did you learn what you know, or think you know, about business and profits? How much came from talking heads in the media, religious leaders, and ivory tower types like sociology professors – people who, for the most part, know nothing about economics and have never run so much as a hot dog stand? And how much

came from businesspeople and economists, who actually know something about the subject? Do you think there might be a problem here?

"In America, the idiot has as much right to spout off as the expert, and often gets more press. That's the price of free speech. But if you've been infected by the anti-business mindset that has resulted, you have to get over it. Not just because this "evils of business" rant is 15% fact and 85% nonsense, but because that mindset is self-defeating. Hating the employer who provides your paycheck is hardly a good foundation for a successful career.

"Here's the straight dope: things (materials, time, shop space for a given period etc.) have value. The value of each is set by the marketplace – that is, by people. What you make or do has value to people, and what you use up in the process also has value. Profit is the proof that what you put out is more valuable than what you use up. That's a good thing, right? If people value your finished product more highly than the raw materials you used, that means you've done something that benefits the public, right? Good. You now understand more about economics than the average sociology professor.

"Yes, I know, this is a rose-colored view. Many businesses do use dirty methods to make money. As I said, 15% of the anti-business rant is fact. It's also a simplification: if the people who make rotgut whiskey are making a profit, does that mean they're performing a public service? The answer involves a discussion of who has the right to decide how other people ought to value things, which is a political discussion, so I won't go there.

"Pull the focus back to you: if you study hard and really master this electronics thing, you will discover that there is more than one potential employer who wants you, and that gives you the freedom to choose one that operates honestly and gives the customer honest value for their money."

EARNING THE PAYCHECK

To continue from EM1:

"(Your paycheck) comes to you because you produce something that's more valuable to your boss than what you cost him. Not because you need it, want it or think you're entitled to it.

“If you haven't yet entered the workforce, it may not have occurred to you that an employer *cannot* pay workers more than they create in monetary value. In fact, he can't pay more than a fraction, because things like rent, insurance, advertising, taxes, the cost of regulation, and the purchase cost of whatever the company is selling must also be paid.

“If you ever thought that a tech's income is or should be tied to any factor other than what the tech produces, put it out of your head. Your employer is not a welfare agency. Let me say that again: *Your employer is not a welfare agency*. He does not owe you a job because you need a job; he does not owe you a wage of so many dollars per hour because that's what you think is fair; he has no duty to worry about what you want out of life. You are just as much a businessman as he is; you have a product and it's worth a certain amount to an employer, and if that amount is not enough to satisfy you then you can't work there.

“I know what I've just said is open to debate, but it's a political debate, mostly argued by people who don't know jack about money and business, and we're staying away from politics. Pull the focus back to you: you, personally will do best if you take the position that your boss owes you *nothing* beyond market-rate payment for your services.

“The way to get more is to be worth more. Become more skilled, more efficient, more reliable, more productive. As Larry the Cable Guy would say: “Git-R-Done!” Git-R-Done, Git-R-Done, Git-R-Done! Make it your personal motto.

You're already on the right track, learning about electronics and getting credentials. Techs, especially the most highly trained ones, are in demand. If you can create a lot of value, you can demand a lot of money.

“There is an important side benefit in relying on nothing but your own productive value for your income: you own your life. Someone who is dependent on others' generosity does not own their life. What they have is decided by other people. It may be sufficient or even generous, but it is not under their control; they have to take what others are willing to give them.

“Now, if you get to the point of running your own business, you should care about your employees for good business reasons. The boss who doesn't care how employees feel about their job isn't being unfair, but he's being stupid. It doesn't cost anything to be nice to people, and a worker who loves their job will do it better.”

But please tell me you're not planning to start your own business right away. Work for somebody else until you know the ropes. Maybe you'll fall in love with the boss' kid, and then you won't have to start your own business. ☺

As alien as it may seem to you now, you need to develop a profit-oriented mindset, and provide good value for the money you're getting – hour by hour, minute by minute.

DEALING WITH PEOPLE

Dealing with people is both an art and a science. The biggest part of dealing well with people is choosing to make the effort, and simply being aware that small differences in how you treat them make a big difference in whether you get what you want from them.

YOUR CO-WORKERS

You know, I could really get to like this cut-and-paste business. Makes me look like I'm working harder than I am. From EM1:

“This is a delicate subject, because I have to talk about the way some people are raised. In your neighborhood, you may need to keep your guard up all the time, because someone may attack or take advantage of you.

People think this is a problem primarily in lower-income, non-white neighborhoods, but a lot of elementary, middle and high schools have that culture even in the wealthiest areas. Growing up in that environment may have taught you that everyone is someone you have to be wary of, and you need to be ready to fight at the drop of a hat.

'I'm not going to call you an evil person for that. You're doing what life has taught you to do. But that attitude absolutely does not work in the workplace, and you have to get rid of it. A company cannot survive if its employees are wasting their energy grinding on each other. They have to be a team.

“I hear you saying, 'That's nice for the future, but how can I let my guard down in the hostile environment I'm in now?' You're not in that environment all the time. Somewhere, you can find a place where it's safe to let your dukes down and practice living in peace with the people around you.

“Or you can make such a place. Electronics students tend to be nerdy, so maybe everybody in your class has been picked on and you've all developed pit-bull reflexes. You should all come to an agreement that the electronics classroom is a refuge, a place where nobody takes unfair advantage of anybody else, nobody needles anybody else or makes fun of somebody who doesn't understand something. Those who get ahead help those who fall behind. When somebody does something brilliant, everybody celebrates.

The ancient Greeks defined what a 'good person' is, and one of the central characteristics is *good will* – wishing other people well, being happy for them when they succeed.

“At first this may be an act, a costume you put on when you enter the electronics classroom. Doesn't matter. When the whole group puts on this act, they discover that it's a better way to live, and it becomes real. A second 'you' is born, a good-natured, helpful, non-aggressive person that you don't dare show on the street, but you let out in this one place.

“Pretty soon you start to attract a group of good-natured, helpful, non-aggressive friends. Wherever you meet up, you create a kind of invisible force field. You may be in a room full of people who are like the old you, but you're not dealing with them very much, you're dealing with your circle of friends who respect themselves and each other.

“I don't mean you should kiss up, kiss-ups are offensive. I mean you should find people you don't have to be wary of, who aren't out to one-up or sabotage you, and build a new social and work life around these people.

“This is one of the big secrets of life: there is more than one human environment, and you can choose. If you're just reaching adulthood, you may not have had that chance yet. A kid is stuck in whatever environment he or she was born into. But kids become adults, and you in particular are going to become a skilled adult earning a respectable salary. That will give you the freedom to choose where you live and who you associate with. If you like an environment full of good-natured, helpful, non-aggressive people, you can have it.

“But to be with them, you have to be like them. Second You has to become Real You. That takes time and practice.

“One other thing you'll discover as life goes on, but it's better if you discover it now: turf wars are stupid. They might make sense in the context of a kid in a neighborhood where turf is limited, but as an adult with valuable skills your turf is the whole USA, as long as you're willing to share it.”

That's what I said in EM1. If you're seeing this now for the first time, when you're about to get certified and start looking for a job, you don't have time to practice. You need to decide, right away, that you're just going to assume the people you will be working with are good folks until you see evidence to the contrary. And you're sure to see it now and then, because every workplace has its share of jerks. More on that:

“So you have a nice job in a good work environment, and then some jerk comes along and spoils it. Somebody with a huge ego, a chip on their shoulder, devious political methods and the belief that the way to succeed is to sabotage everybody else. Somebody who hasn't grown out of the turf-war mentality. Somebody who only keeps their job because their value to the company outweighs the damage they're doing.

“You need to disarm the jerk without getting dirt on yourself. Old You would maybe pick a fight. New You looks for a way to avoid a fight, a way to rise above the stupidity. The best way to do that is to insist on being the professional you've been trained to be. Explain with a polite smile that you have no patience with this kind of bullcrumbles, you're there to do a job and that's what you intend to do.

“Or you could complain to the boss. This is a last resort. Nobody likes a tattletale, even the boss. A polite *threat* to go to the boss works better. 'George, I have a job to do, and if you keep this up, it isn't going to get done. The boss will ask why it didn't get done, and I will have to say somebody kept getting in my way, and he will ask which someone and what they were doing, and I will have to tell him. That will lead to more problems. So let's not go there, okay?'

“Or try this: 'George, this thing you're doing is hurting the company. You know that, right?' Of course he knows it, but he didn't think anybody would say it in so many words. Once you do say it, if he's got any brains, he can figure out what might happen next. The aim is not to get him in trouble, it's to get him to take his petty games somewhere else.

“If he's deliberately needling you, don't rise, that's what he wants. Remember the old saying: they can't get your goat if you don't show them where you keep it.

“Taking evasive action may seem un-macho. But I've seen enough wars, both the bomb-and-tank kind and the personal kind, to know nobody wins a war. The “winner” is just hurt less than the loser.

“Imprint these four words on your mind: 'Take the high road.' Always take the high road. Since I'm doling out maxims, here's another one: if you wrestle with a pig, you may win or the pig may win, but you'll both wind up covered with mud.

“I'm about retirement age, so I'm looking at my career from the other end, and one thing I would want to tell everybody just starting out is to always take the high road. Sometimes you'll lose because of it, but when I've lost out on a deal because I took the high road, I've later discovered the people or situation were not on the level to begin with and I was lucky not to be part of it.”

DEALING WITH THE BOSS

As I explained in EM1, for practical reasons, in this chapter only I'm going to abandon gender-neutral language and speak of the individual as “he.” It's a fact that most people in electronics are male. It's also a fact that this is beginning to change. High time.

If you have as much self-respect as I hope you have, you will find it hard to adjust to taking orders. Keep in mind that this is not a master-servant relationship, it's a seller-buyer relationship. You are the seller, the product is your skilled labor, the price is your hourly wage or salary, and the boss is the buyer; that is, your customer. Being a good employee makes your product worth more.

Your boss has a right to *all* the time he's paying for. Suppose you were to walk into McDonald's and order a meal. Suppose they told you the fry machine was broken so you wouldn't be getting fries, but they were still going to charge for the whole meal. No fraggin' way, you'd say, that's a scam. But that's what you're doing when you're paid for an hour, but you spend ten minutes of it on the phone with your GF / BF. People in your life must be instructed, bluntly if necessary, not to call you on the job except in an emergency.

The boss also has a right to give directions and expect them to be followed. I used to work in a shop where, at 8:00 A.M., the shop manager would assign my task for the day. At 11:00 A.M. his boss would come to me and say, “Stop working on that and work on this.” Then at 2:00 P.M. *his* boss would come to me and say, “Set that aside and work on this.” End of day, three projects started, none finished, and the shop manager would get yelled at.

Does that seem fair? And it's more than unfair, it's a business fail. When a problem is blamed on the wrong cause, the wrong cure will be applied, and the problem won't get fixed.

It would be hard to think of something more idiotic than letting one person call the shots and holding another person responsible for the results. Authority and responsibility go together. Your boss has the right to give instructions and expect them to be followed because he's the one who takes a hit to the bank account (or gets yelled at by *his* boss) if things get messed up. (On the other hand, if there's something he's not aware of, which will throw a monkey wrench into his plan, you should let him know.)

Will your boss be everything a boss should be? Don't bet on it. After a while, you may start to wonder how it happens that most of the world's bosses are bozos.* Here's how it happens: everybody has faults. The boss' faults aren't any worse than anyone else's, but he's in a position of authority so they are magnified. That's the thing about authority: only an exceptional person is really qualified to exercise it. There aren't enough exceptional people to go around, so most bosses aren't what they should be. You have faults too. If you were the boss, they would be magnified the same way. So cut the guy some slack.

(*As opposed to Bezos, who runs Amazon and is not a bozo.)

DEALING WITH THE CUSTOMER

Sociology professors like to make a lot of noise about how much power big companies have, how they lord it over us and blah blah blah. They've got it completely backwards. Anybody who's in business knows (or learns the hard way) that it's the customer who holds the power, and the business must treat him as a commoner would treat a king.

His Imperial Majesty The Customer may be a part-time janitor with five bucks in his pocket, but when it comes to spending those five bucks, he has absolute authority. How he chooses to spend them is completely up to him. He can be as whimsical, irrational and arbitrary as he chooses, and there's no court of appeal. If he decides he doesn't like the shape of the doorknobs on the rest rooms at McDonald's, he can take his business to Burger king.

When you deal with a customer, the most important thing to keep in mind is that there are hundreds of other companies who want his money as badly as yours does. You have no special claim on it. Whether you think you deserve his business is irrelevant. The only thing that matters is what *he* thinks. That being the case, the only way your company can get his money is to offer such a good value, and such a pleasant buying experience, that it trumps whatever those hundreds of other companies are offering.

If you work for a big company, don't think their size insulates them from the need to win the customer's favor. J.C. Penney and Sears/Kmart are big companies, but they haven't been very good at attracting customers lately and look at the trouble they're having.

Get used to saying “Sir.” If you're a proud sucker like me, the first few times you'll have to force it out of your mouth. But you have to call the customer something and “Hey, you!” doesn't cut it. Someday you'll be his customer and then he'll call you “sir.” For a female customer, “Madam” is either too formal or too suggestive of someone who runs a house full of easily persuaded girls. Too high or too low, either way you lose. Say “Ma'am.”

When you deal with a customer, you are selling two products: whatever your employer is selling, and *you*. If you are a friendly, upbeat, helpful (but not kiss-up!) person with an obvious desire to do right by the customer, he may decide to do business with you based on that alone. Many customers make buying decisions more on personal factors than on the quality or value of the product – though if you told them so, they wouldn't believe it.

When you do win a customer's favor, don't get lazy. Each time you deal with him, you might do something wrong, tick him off, and lose him forever. Remember that you and your company are *always on trial*. You must not only try to please the customer, you also keep a sharp eye out for things that might displease him – a customer is often lost over a trivial irritation.

When you deal with a customer, you're not just trying to make a one-time sale. You're trying to build an ongoing relationship. My mom is a painter (still active at 97!) and probably 2/3 of her sales come from repeat customers who bought one painting, then became collectors, then friends. Whenever she has a show, she goes through her list and sends out postcards. Many of her best customers get Christmas cards, and she gets lots of cards in return. *A successful company is built on repeat business. Repeat business is built on personal relationships.*

What I've said may not match your experience. Front-line employees often do not understand how extremely important it is to please the customer. Some business owners get so wrapped up in their company that it means everything to them, and they don't understand that in the lives of the people walking by on the sidewalk, it means nothing. I've seen amazingly few companies that really know how to treat the customer properly. And that's a really good thing for you, because if you treat the customer right and your competitors don't, you can eat their lunch.

DEALING WITH THE TIME CLOCK

I have no love for the traditional classroom, but one thing it does teach is to be on time. I'm just a little worried that, with flexible learning – which is a great idea, for the most part – techs are going to start their careers without ever learning how to stick to a schedule.

When you're reading this study guide and you decide to can it for the night, that's on you. But an employee is usually part of a team, and few businesses are sloppy enough to keep and pay someone the team doesn't need. The fact that you work there means you're necessary, and when it's 8:15 A.M. and your team is waiting to go to a job site and you're not there, it screws everybody up. So be on time.

If you can't handle that, then you need to find a tech job where you work on your own and nobody cares if you start at noon, take four hours for dinner, and finish at midnight. There are jobs like that; I have one. But this will very seriously limit your choices, and probably your income.

PERSONAL APPEARANCE

There are also jobs where your appearance doesn't matter, but you're not there yet. People just entering a profession need to prove they are professionals, and looking like one is a big part of the game.

There used to be a rule that a professional either wore a white shirt and tie, or a uniform. The rules have changed, in part to accommodate women entering the work force. There are informal workplaces now where wearing a tie will make people think you're an alien species. The rule now is: look at what other employees are wearing and wear the same stuff, and always keep it neat and clean.

That also extends to your person: trimmed hair, clipped, clean fingernails etc. This is not only to show respect for the boss and the client, though of course you must do that. *It's also to get them to show respect for you*. Appearance, and especially first impressions, powerfully influence people's idea of who you are. Your appearance should say, "I am a professional, and I should be treated and paid like one."

Specific items:

- Tie: should end ½ to ¼ inch lower than the top of the belt buckle. Real around-the-neck ties are the most "respectable," but if you work around rotating machinery, safety is more important, wear a clip-on. A tie clip is better than a tie tack because if the tie gets caught in something, it will pull off. Bow ties are never worn nowadays except in the most formal situations.

- Jewelry: keep it modest. Wedding ring, watch, small earrings for women. Blingy jewelry says “pay attention to me, never mind the company.” Piercings are a no-no unless the boss also has them. Jewelry should be removed when you're working in a situation where there's any chance it could cause an accident or injury.
- Shoes: black is best unless another color is part of the uniform. Keep shoes polished and in good repair. People judge you by your shoes and fingernails a lot more than they maybe ought to.
- Belt: same color as shoes.
- Socks: black or dark blue. A prominent pattern is a bit weird in the workplace.

By law, your employer is prohibited from dictating many personal appearance details, but the customer is not so constrained. Many customers are uneasy with some modern dress styles. Your job is to help your employer make a profit. That's the only thing that gives you a right to be there, and certainly the only thing that will win you a promotion. Express your Goth side in the evening, on your own time.

COMMUNICATION

I know a lady who works as a junior officer at a bank. She dresses smartly, has stylish hair, and knows what she's doing. But she says “dese,” “dose,” and “youse,” and she will never be president of that bank.

I hope you're not the kind who will be satisfied staying in your first job for your entire career. You'll want to advance. And if you never learned to speak “proper” English, the more of a roadblock it will be the higher you go.

Make a point of communicating as clearly and properly as you can. Listen to good speakers and pick up their habits. You may even want to consider taking remedial grammar classes. If English is your second language, learn to speak it perfectly – that always impresses people.

When you meet someone, introduce yourself, say who you work for and the reason for your call. Experts recommend that you use the other person's name often in conversation. I'm not sure I agree; you can come off as a greasy schmoozer if you do too much of it. At any rate, use the person's last name and title, not the first name, unless they ask you to or until you get to know them.

Develop a sensitivity to the underlying meaning of words. The word “plump” means the same thing as “obese,” but the latter also implies criticism. There are always several ways to say something, and that's where the art of diplomacy lies.

Don't say “I don't know,” say “I can get you that information.” Don't say “You don't understand,” say “I need to explain this better.” A product is not “cheap,” it's “inexpensive.” Or if it isn't inexpensive, then it's “deluxe” or “first class,” not “expensive.” Don't lie, but do spin just a little.

Never, ever utter profanity in the presence of a customer, even if he swears like a tugboat captain. It's best to stop swearing completely, and I have a personal reason for saying that. Up through high school, I was the proverbial good little boy. Then I went off to college, and my language got a lot more colorful. When I came back home, some things slipped out of my mouth that surprised me as much as anybody. Mom was not at all impressed. Grandma almost had a stroke. I'm sure she was thinking, Who is this pig and what has he done with my grandson?

Word to the wise: churches are buying a lot of electronic stuff these days, so there's a good chance you will wind up working for a company that does business with them. The biggest electronics buyers are the large, religiously conservative, fundamentalist churches. Accidentally drop an F-bomb there just once, and they are likely to decide you and your company do not fit their preferred supplier profile. That could be a fifty thousand dollar accident.

And it could just as easily happen outside that church, when you're dealing with one of its religiously conservative members in a different context. You never know.

Watching your mouth when you're with a customer is extra work, and who needs that? Take the lazy way out and just eliminate those words from your vocabulary.

TELEPHONE TECHNIQUES

I used to like to eat at a Mexican restaurant in St. Paul that had good food, good service, nice atmosphere, reasonable prices and the best Chile Con Queso in the world. But if you called them on the telephone, you got rude, inattentive treatment that suggested a completely different restaurant, one you wouldn't want to eat at. And that apparently frosted enough people that I can't go there any more, cuz they're out of business.

When a new, might-be customer calls, they may know absolutely nothing about you except how you treat them on the phone. The caller is a casting director and you're trying out for the role of supplier to them. I shouldn't have to give you a list of detailed do's and don'ts, you just need to put yourself in place of the caller and ask yourself what kind of impression you're making. Are you treating them the way you would treat them if they were in the room with you?

One specific thing: when you give a number, repeat it. This is especially true if you're leaving a recorded message.

BODY LANGUAGE

Don't slouch, and don't stick your hands in your pockets, it suggests laziness or dishonesty.

Experts disagree about making direct eye contact. My preference is to make eye contact but stand far enough away so as not to seem threatening.

Yes, people really do judge you on this nitpicky stuff. Don't blame them, it's not their fault, they're not aware they are doing it. It's their subconscious at work.

By now you're about ready to scream. It probably seems like I've been teaching you how to become a robot, and a suck-up robot at that. But someone who hires a tech is not usually looking for a robot. They want the very best of your human ability to think, reason, plan, create, and interact with others at the highest level. Which is precisely why personal quirks that get in the way must be banished.

I've said enough about personal issues. Let's talk about how a shop is run. I'm going to use a repair shop as an example, but a lot of this applies to any kind of business.

STAYING IN BUSINESS

Someone who has never run a business has no idea how fragile profit is. A little inefficiency here, an unexpected loss there, and profit goes to zero. Let's say the company you work for makes a net profit, after all expenses and taxes are paid, of 10%. Suppose everybody gets sloppy and lets expenses rise 10%. 10% isn't much, but it wipes out 100% of the profit. That's why when something goes just a little wrong, the boss stomps around with fire coming out his ears. It's also why he makes a big deal about little improvements in efficiency. He may be driving a Mercedes today, but he could easily be bankrupt tomorrow.

Never imagine that it's easy to keep a business afloat. Something like 80% of new businesses go belly up within five years, and the companies that owned the consumer market when I was a kid – Woolworth's, Sears, J.C. Penney and Montgomery Ward – are gone or in serious trouble.

PRODUCTIVITY

There are many ways to measure productivity. Even in the same business, different operations are measured differently.

For a technician, productivity is usually measured by how much time is spent on activities that can be billed to a customer versus time spent in cleaning, organizing, maintenance and similar activities that do not directly result in revenue:

$$\frac{\text{Billable time}}{\text{Total time}}$$

Suppose you work 40 hours a week and 30 hours is billable. Your productivity is 30/40 = 75%.

Usually, when a customer pays the company $100 for a tech's labor, $30 goes to the tech, $30 goes toward "overhead," which is the costs of doing business – heat, light, rent, insurance, advertising, salaries for the office staff, taxes etc. That $30 also pays the techs during times when they are not directly earning revenue. $30 is reinvested in the business, to keep it competitive. This is known as the 30-30-30 rule. The remaining $10 goes into a contingency fund that is used to cover unexpected expenses, which seem to come at you from out of nowhere and happen to every business.

In a business that operates on the 30-30-30 rule, break-even productivity is 60%. If at least 60% of a tech's time is not directly billable to customers, that tech is not making the company money but losing the company money.

The reason productivity is so important is that overhead – rent, utilities, taxes, insurance etc. – is not flexible. Overhead is often called the "nut" because it's a hard cost that must be paid no matter whether business is good or bad. Likewise, the company has agreed to pay its employees so many dollars an hour, and can't usually get away with shaving that figure. This means, when expenses rise or revenue declines, it's the profit and re-investment fund and the contingency fund that take the entire hit. Productivity doesn't have to go down very far for profits to go down to zero. At that point, the company goes bankrupt and you lose your job.

As an employee, you are not in complete control of your productivity. But to the extent that you are, be as productive as you can. Spend as much time as possible on billable work. At other times, clean, organize, restock, and make sure you have an adequate supply of critical materials. Few things mess up profits like making a special trip in the middle of a job to fetch something you've run out of.

NEW INSTALLATIONS

If your company does new work, installing systems and so on, the project will be planned by management and they will hand you a stack of paper (or an e-file) that spell out what you have to do.

For the most part, you just do it. But keep records anyway. Have a notebook where you write down how long it took to do this and that. Also write down any hitches you run into, and how much time it takes to deal with them. For an employer, having this info for future reference is extremely valuable. For you, if you do this consistently, it may occur to your employer that this is the way a management person acts, and you should be a manager. And if you ever run your own shop, knowing this stuff will greatly improve the chance that your business will survive and prosper.

A word about **change orders**: it is common for the customer to request changes and additions on the spur of the moment, from on-site workers. He's expecting you to say, “Sure, we'll just do that while we're here.” But that's not what you say. You say, “I'll call my boss, I'm sure he'll be happy to arrange it.”

Rule of thumb: change orders that go through the system and are properly documented are money makers. Change orders that do not are money losers. At the very least, be sure the customer is willing to pay for the extra time at the normal hourly rate.

RECORDKEEPING

Okay, I admit it. You hate to bother with recordkeeping? I hate it worse. I don't keep all the records I should, and I have not the slightest doubt that I've suffered aggravation and lost money as a result.

If you fill out the paperwork neatly and completely and hand it in promptly, your boss may go into a dead faint from astonishment. A tech who has mastered both electronics and recordkeeping is such an awesome being, other techs will tremble in your presence. (Or they'll resent you because you're better. Some people are pretty small-minded.)

Records are the foundation of business decisions. A company that doesn't have proper data is like a raft adrift in the ocean. At the very least, the boss has to know whether the company is making or losing money, and that takes data that comes from records.

If your boss is smart, he'll want a lot of different kinds of records, and he'll spend a lot of time going through them. This is called “data mining” and it means collecting information that can be used to increase sales and profits. A company that doesn't do it is at risk of being plowed under by companies that do.

Billable Hours

Most companies bill their work at an hourly rate. Even if a company doesn't, even if it bills a flat fee for a certain service, it needs to know how much time is actually being spent on each job so it knows whether it's setting the flat fee correctly. It is also used to evaluate an employee's effectiveness. That may sound scary, but suppose you're one of the better, more efficient employees – there's a strong likelihood, you know – don't you want the boss to know you're not the reason the service department is losing money?

Job File

When your company installs electronic equipment for a customer, it's your company the customer will call when something breaks six months later. After six months and however many other jobs, you won't remember exactly what you did. If you didn't make charts and diagrams, you will be in the embarrassing position of having to re-learn your own work. This will also double the repair time, and if the system is still under warranty, that's a cost you'll have to just eat.

For anything but the simplest system, you should have a file that includes:

- the contract
- correspondence between you and the customer.
- information and comments about customer (e.g. “loves shiny, brushed aluminum panels”)
- blueprints or other records of the system design.
- details of the system as constructed, including interconnections, connector types, a block diagram showing every cable, and whatever comments would be of use to a service person. If there's a note like “25-foot ceiling,” the service person will know to bring a tall ladder.
- copy of owner's manual for each piece of equipment.
- invoice and payment record.
- warranty information.

When the system is installed, you need to fill out all those warranty cards and send them to the manufacturers, but you also need to put warranty information in your own file. If a unit conks out and it's in warranty and you can prove it, the manufacturer will reimburse you for the cost of repair.

Best of all, records like this can tip you off when it's time to call the customer and recommend updates / upgrades. Without records, a customer may represent a one-time sale. With records, you can turn this into a lifetime relationship that results in sale after sale.

Scheduled Maintenance

In a system of any complexity, there are things that are guaranteed to need servicing, not because they're crummy but because that's just the way those things are. Projector lamps dim and burn out, fans get clogged with dust, etc. Be thankful for these things, because they are the reason your customer needs a **maintenance contract**, and maintenance contracts mean a steady income stream. If you can't sell one when the system is first installed, you probably can after its first failure.

But selling a maintenance contract is like stepping out onto a high wire. You really have to perform. You're charging to keep the system in top shape, and the customer will expect it to work flawlessly all the time. If it doesn't, you may have to do a free service call. This means you have to make a list of where all the potential problems are and how to head them off. You absolutely must have good records, including a file where you specifically list every maintenance task that must be performed during every visit.

Inventory

Discovering you've run out of a certain kind of part just when you need it most is galling. There are two ways to avoid that. The less efficient way is to take inventory every week. The better way is to have a place in your job ticket where you note the things you've used up during the job, and a procedure where the office staff orders replacements.

Planning and Profitability

Detailed time and cost records allow management to determine whether the business is making money. It also shows trends, permitting management to make decisions about expanding or downsizing each aspect of the business, or identifying new opportunities.

Taxes and Regulations

If you're thinking of ever going into business for yourself, fair warning: the amount of paperwork required by government is huge. While a lot of that is never seen by the tech employee, you do have to keep track of time and materials for tax purposes. A business pays taxes on its profit, which is revenue minus expenses. Any expense you don't report is an expense your employer can't deduct. In a sense, the business has to earn its money twice: once from the customer, and again from the IRS.

Following is a list of specific records a typical shop would keep. Each kind of record involves a form to be filled out.

For a very small business, this may be a standard form bought from an office supply store, but with the ease of making forms on a computer these days, most shops roll their own.

Service / Repair Ticket

This is the basic record in a service shop. The job starts with the following information being filled out, either by the tech or by office staff:

- Who: client's name, phone number and email address
- Where: client's address, even if the unit is being serviced in the shop (because you have to know where to send the bill)
- What: the unit or system being serviced
- Why: the nature of the malfunction, including any information you can get on circumstances

As the tech works, the following information is filled in:

- parts used. This allows the employer to bill the customer, and to re-order, so you don't run out of those particular parts.
- hours spent. This allows the employer to bill the customer, pay you, and keep records required by government.
- nature of repair. This describes what went wrong and what you did to fix it. This info should be as complete as possible, because the next time something goes wrong, it will be useful to look back and check the history. If the same thing keeps breaking, there's an underlying problem you need to find.

When the job is in progress, the service ticket is “open.” Once the job is completed and the needed information filled in, the ticket is “closed.”

Invoice

This is the bill prepared from service information and sent to the customer for payment. In some cases the service ticket serves as the invoice.

Customer Record

This is a file which, ideally, contains all the important information from every encounter with a particular customer. Some of this info comes from the service ticket. Some of it is private commentary, as in “customer likes all equipment to be mounted in a rack.”

FILLING OUT FORMS

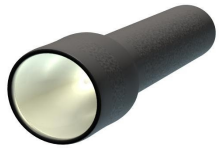
There is only one “proper” tool for forms, and that's a ball point pen with black ink. Blue ink does not show up well on photocopies, red and other colors are unprofessional, and pencil or any other erasable kind of writing is unacceptable where contracts and money are involved. Felt-tip markers are only okay if their ink is permanent, and if you're using multiple-copy forms, you can't press hard enough with a felt tip to make a readable impression on the bottom copy. Use black ink pens only. Keep a good supply everywhere you work because you will lose them.

To end this chapter, I want to say some things that will help you be a more efficient service person.

WORKPLACE ORGANIZATION

The most important thing I can say about your workbench is not to let stuff accumulate on it. Cleaning and organizing is a bore, and I personally can't claim to be a poster child for neatness, but if you can get close to always having a clean bench, it will pay off.

The bench should have general lighting, a task lamp on a movable arm, and a bright LED flashlight or two. It should have enough outlets that cords don't have to drape across things, and it should have a master ON/OFF switch so you



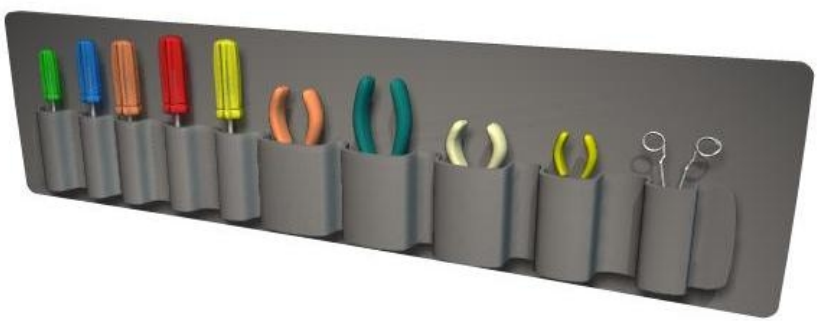
can kill everything at once when you go home at night. The lights should be on this switch so there's no chance of forgetting to turn the power off.

Studies show that most techs waste a huge amount of time looking for tools. Next to my bench, I have three large, shallow drawers holding screwdrivers (sorted by type & size), cutters & strippers, and pliers & wrenches respectively. Other tools are sorted into bins by type. I almost never have to look for tools. I also have a slide-out tray under the bench that I can sweep parts or debris into, then empty.

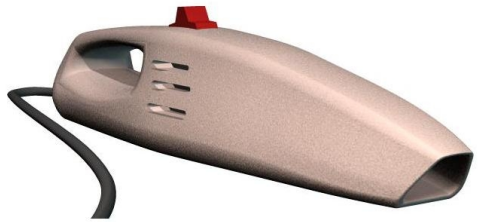
Lubricants should be kept in a tray by themselves, because they always seem to slobber on other things. Solvents should be kept away from the bench entirely, ideally in a metal cabinet with a door, one designed for the purpose.

A solvent brought to the bench should be in a push-top can that only dispenses a little at a time.

In the field, it's worth having a roll-up tool holder with pouches, instead of just dumping tools in a box. You will get so familiar with it that you can reach out and grab a tool without even looking. It looks good to the customer too.



I'm astonished at how few field techs bother to have a hand-held vacuum to clean up wire clippings etc. No matter what you do to impress a customer, it will be shot down if you leave his premises without cleaning up after yourself.



DIAGNOSTIC TECHNIQUES

“Diagnostic” means “figuring out what the &#% is wrong with this piece of @)%#!” Oops, sorry, we weren't going to use that kind of language any more.

So someone calls you up all in a panic, their thingy has stopped working and you gotta fix it right now! How do you proceed?

Well, first, you take “right now” with a grain of salt. When a job is rushed, it's often done poorly, leaves the shop's orderly work flow in disarray, and requires second and third trips to correct things that were overlooked the first time. After this happens enough times, you'll know when to politely say “I'm sorry, it will take a little longer than that.”

The proper time frame is as soon as possible without causing upheaval in the shop and mistakes on the job site. I'm going to call the person who called you a “customer,” even if that's someone inside your own company. The customer is your best diagnostic tool, because they have information that will help you zero in on the problem. You need to ask a bunch of questions.

- Please describe the problem.
- Is this the first time this has happened?
- Did this problem happen as soon as the equipment was turned on, or was it running for a while first?
- (If this has happened before) Is this problem random, or is there a pattern? Does it happen when you do a particular thing? Can you make it happen again?
- Have you installed new software or changed the physical configuration recently?
- (If it's a system with parts in various places in the building) Has there been any construction or remodeling work recently? Have you seen electricians or plumbers on the premises?
- Did this happen after a big lightning storm or brownout?

Suppose the customer tells you there's been some remodeling. Carpenters will chop data cables and not even tell you. Likewise, the answers to other questions will give you clues. One of the Great Truths Of Life is that finding the right answer is mostly a matter of asking the right questions.

If the customer caused the problem, they may be too shamed or too fearful for their job to tell you. Watch them closely. If they say, “No, I didn't do that,” their body language may say, “Yes, I did do that.” This may tell you how to fix the problem. It will also tell you that, once the problem is fixed, you need to say what the problem was in a way that won't embarrass them further. The line, “Everybody does that now and then, I do it myself” is useful, even if it's not true. Help them save face in front of their boss, and they will join your fan club.

Large data systems automatically make records of alarm and system function data, and they can show you what was going when the malfunction occurred. If a particular operation caused the malfunction, you may be dealing with a software bug. It might be something as simple as the system running out of capacity during periods of high demand, or maybe operator error. These are problems that would be difficult to diagnose without those records. Make use of them.

As a rule of thumb, don't be too eager to start removing screws and taking panels off. Taking everything apart, and then finding out that the problem isn't in the hardware, is embarrassing and hard to explain to the boss.

Once you do start taking things apart, make sure you store the screws in a safe place. I use a pill bottle with a screw-on cap. Some people use a plastic tackle box with compartments, to make sure the screws go back in the right order. This keeps you from mixing up, say, ¼ and ½ inch screws. Whatever you use, it should have a tight-fitting cover or cap. You may have to set the unit aside for a few days while you're waiting for parts to arrive, and you don't want any possibility of knocking the screw container over and losing the screws.

Now and then you'll find that a unit is beyond repair. If you work on that kind of unit a lot, don't just throw it out, keep it around so you can scavenge replacement parts. Lost screws, for example.

ISOLATE THE PROBLEM

A sound system guy I've worked for a long time says that when someone brings in an amplifier for repair, 80% of the time there's nothing wrong with it and the problem is somewhere else. What that someone failed to do was to **isolate the problem**, to perform various tests to see whether the problem is in the most obvious unit, or something upstream or downstream from it. Don't just try various random things or assume the problem is with a certain piece of equipment. You can usually perform simple tests to narrow down the possible area of the problem, like a hunter cornering prey, until you reach a point where you can say, “The problem is not there, there or there, so it has to be *here*.”

You'll often be able to narrow it down to a single component, and then a simple swap-out will restore the system to operation.

Several ways to isolate a problem:

- Disconnect parts of the system from each other and see if the parts work individually. If they do, check out the cables that connect them.
- Swap a unit with a known good unit.
- Disconnect a signal source and substitute a known signal from a signal generator

USE YOUR SENSES

You have five senses. I wouldn't encourage you to taste pieces of equipment, that's kind of strange and your co-workers will start to look at you funny, and anyway it's not much use. But do use the other four. They amount to a set of test gear that's quick, sensitive, always at hand and free.

Vision: check for signs of damage. Is a corner bashed in? Do you see coffee stains? Do any of the cables look like they've been pulled halfway out of their connectors, like someone has tripped over them? If you're looking at a PC board, components that overheat often fracture and pieces fall out. Electrolytic capacitors can burst, spewing fiber insulation around. If something has been too hot for a long time, the PC board under it will be charred or discolored.

Smell: hot things smell hot. If they're burned, the smell will have an acrid edge to it. Very high voltage produces ozone, which smells like fresh air. Some things produce ozone normally, but it can also indicate malfunction.

Hearing: machinery makes loud buzzing and humming noises, but electronic equipment usually isn't supposed to. Loud humming plus a hot smell usually indicates trouble. A CRT monitor – yes, people still use them – often whistles or crackles when there's something wrong with the high voltage circuit. Noisy motor bearings almost always indicate trouble, though ball bearings normally make some noise.

Touch: careful with this. You're looking for heat, and sometimes you'll find a lot of it. Silicon transistors can work fine at a temperature that would boil water. After you've been on the job a while, you'll know what is normal for a particular piece of equipment. Note that when a component is hot, it doesn't necessarily mean that's where the problem is. For example, if an amplifier is trying to drive a shorted line, the amplifier will overheat while the line remains cool.

When troubleshooting a PC board with lots of components, a quick finger check may locate a part that's overheating because it's shorted. Then again, a shorted component may simply bring down the power supply. Nowadays, most circuitry is powered by regulator chips that shut down when too much current is drawn.

If you find a regulator chip that's hot, most likely it is not the problem. It's hot because it's trying to deliver too much current to some other component, and that's where the problem is. The shorted component may not get hot, because though there is a high current through it, there is little voltage across it, meaning little power dissipated. (You remember Watt's Law from EM1, power = voltage X current.) In this case you can use a very sensitive voltmeter to track voltage drops along PC board traces.

The worst problem to find is the one that comes and goes. The word for that is **intermittent**. If it's a physical problem like a bad solder joint or component, you can often track it down by changing temperature. A service tech's tools should include a bottle of freeze spray, which can be sprayed on one component at a time to lower its temperature below freezing. The radical change often

makes an intermittent component start working again, or stop working completely. Another method is to take an insulated rod and tap on individual components. Once you've found the villain, you can replace it. But keep in mind that it may be a cold solder joint under the component, not the component itself, that's causing the problem.

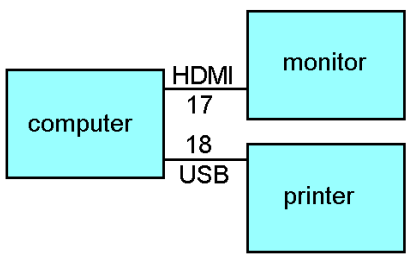
SERVICE LITERATURE

There are two main sources of service literature. The first is the equipment manufacturer. These days, when you can get it easily from their website, there isn't much excuse for not using it. Very often, the solution to a problem is right there in black and white.

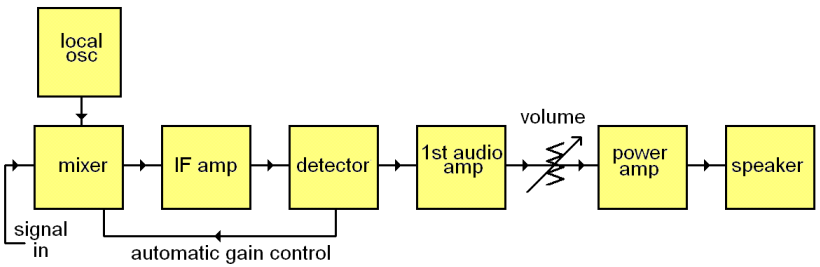
Service literature will also tell you some other useful things:

- Specifications and operating characteristics: how is the thing supposed to work, and what are its limitations? Especially if it's low-cost gear, its "normal" operation may not be spectacular. No point trying to fix it beyond what it's capable of. Also, the unit may not be broken, but maybe it's being used outside its design limitations, e.g. HDMI outputs driving too-long cables. Manufacturers' specs will tell you.
- Operations guide: where's the "on" button, and what the other functions are. Keep a lookout for functions that are not obvious; i.e. that don't have their own knobs. This is often the source of user error.

  For example, home theater equipment manufacturers seem to enjoy burying critical functions in the most obscure menus, six layers deep. Also watch out for units that are incompatible with each other. In some cases, different units from the same manufacturer won't even work together; e.g. a certain manufacturer's DVR and the same manufacturer's video screen. If I ran the world, equipment designers who do this would be forced to run naked down Main Street at noon.
- Interconnection diagrams: how each piece of equipment is supposed to be connected to others. BTW, when a system is installed, identification tags should be attached to both ends of every cable, and those numbers should be recorded on the interconnection diagrams you're making. You can use pre-made number tags, or you can get a label maker machine and label cables with their actual functions.

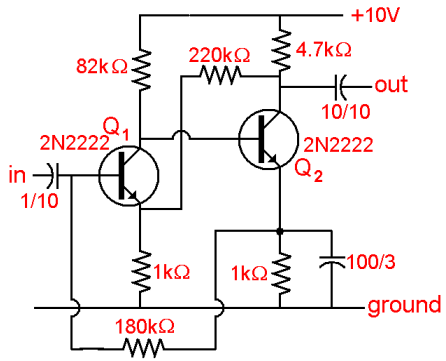


- Block diagrams: what each part of the circuit does, how it connects to the other parts, and how the signal or data moves from one block to the next. This may be a little confusing. I've always thought flow should be indicated by little arrows, but nobody else seems to think so. If you're lucky, the diagram will be drawn so the main functional process flows from left to right.



By the way, the diagram isn't holy scripture. If you defile it by drawing signal-flow arrows and making notes on it, it won't cause your mother to be struck by lightning. Use a pencil in case you make a mistake.

- Schematic diagrams: a detailed picture of the circuit, showing every resistor, every capacitor, every pin of every IC chip. This takes up a lot of space, so expect to see diagrams for complicated equipment broken down into sections, with connection points to other sections. These may be physical plugs and sockets, or they may just be wires that go off the edge of the page you're looking at, with numbers to show you which wire is a continuation of which wire. When I was a bench tech, I had a sort of half-rule that I wouldn't even start working on a unit until I had a schematic in hand.



- A particular type of service “literature” for complicated equipment is the test software written for it by its manufacturer. There's no way you can thoroughly test a complex piece of digital equipment yourself, or even know every test you should perform. Let the manufacturer do the work. Go to their website and download the test program. If there's one available, their printed literature or the website specs for a unit will tell you.

When requesting service literature, the manufacturer will need the model number and the serial number. A manufacturer may make changes during the life of a certain product; two units with the same model number made a few months apart may not be the same inside. So don't neglect the serial number.

The other source of service information is the Internet search engine. It's not likely you're the first person ever to experience this problem with this piece of equipment. There are all sorts of internet forums, some hosted by manufacturers, where people discuss things they've run into.

The internet is also the best source of info when you've got equipment from several different manufacturers and it isn't working together. Each individual manufacturer will have no clue what's going on with the other manufacturers' equipment, but the cloud crowd probably will.

Speaking of which: some manufacturers don't like to release their service literature to just anybody. They want their equipment worked on by their own approved service centers. You may have no choice but call on one of those, but first do a little surfing. One of a tech's *most valuable attributes* is that “Git-R-Done” mindset, the ability and habit of tracking down the information needed to complete a project by yourself if assistance isn't available from people around you (and a good sense of when you should and shouldn't do that).

Diagrams are often laid out poorly, with all the components and their interconnections shown, but no sense of signal or process flow. They say J.S. Bach's way of learning a piece of music by some other composer was to take pen and paper and copy it out note by note. I can recommend that method, because I often redraw diagrams my own way. By the time I'm done I not only understand how the signal flows, I'm also aware of every single component and what it does, and I have a diagram that's laid out more logically.

There's another kind of diagram you may have trouble getting because it may not exist, and that's the system diagram that should have been made by the installer, showing how all the various pieces of equipment are interconnected. If the system is physically a mess, with cables running all over like an explosion in a spaghetti factory, that's actually lucky for you because you can tug on cables and trace the connections that way. On the other hand, if everything is neatly laced up with cable ties, you may have to cut the lacing open to find out where things go. If your job takes you on the road, you should always have cable ties in the truck, even if you're not an installer, because you may have to replace what you cut open. If the installer didn't make a record, try to get the customer or your boss to give the go-ahead to make one yourself. That way, next time the system needs servicing you won't have to go through this exercise again.

NARROWING IT DOWN

The one thing that's common to every part of a given piece of equipment is its power supply. Check to see if it's putting out the right voltages. If not, that doesn't necessarily mean the power supply is bad. Start disconnecting sections of the circuitry. If you unplug something and the power supply comes back up, you've found the section where the problem resides.

On the other hand, if you disconnect the power supply from every load and it still is down, then the power supply is probably the problem. You did check to see whether the power line fuse is blown, didn't you? *Always check the simple things first*.

While it's generally safe to unplug a section of circuitry while the power is on, you shouldn't plug something in while power is on. This is called **hot swapping** and it may blow something out unless the circuit is designed to handle it.

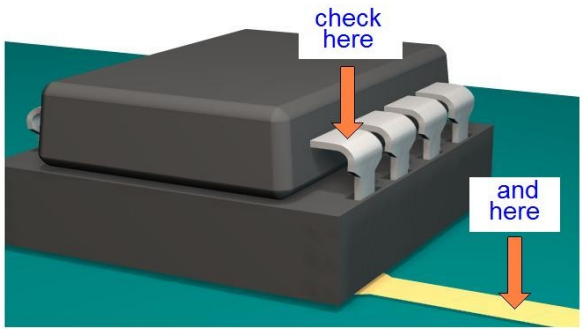
Next: there may be other things common to the whole circuit, or large parts of it, like a system clock or supervisory voltages. Check to see that they're present.

If this is a unit where signal flows from input to output, now is the time to apply the ability you've developed to visualize signal flow. Start by checking the signal itself at the input – is there actually an input signal, is its level correct? If not, disconnect it from the unit you're fixing and test it again. Maybe the unit has a short at the input. If there's still no signal at the input, go up the chain to the previous unit – does it have an output signal? Disconnect the cable between them and check again. Maybe the cable is shorted; do an ohmmeter test. *Isolate the problem*.

If there's signal at the input to a unit, start where the signal is connected into it (or where it originates within the unit, if the unit makes its own signal) and trace it through the circuit, stage by stage. If it disappears or gets screwed up at a particular point, that might be where the problem lies. I say “might be” because sometimes, especially with analog equipment, there will be feedback loops etc and if one part goes out, everything is upset. For example, in audio amplifiers, a DC signal from output back to input stabilizes the operating point. If an output transistor blows, the DC level will change and the input transistor will be shut off. An incoming signal will disappear at that point, but that's not where the problem is.

In cases like this you may have to look at the voltage on every pin of every transistor to find the one that doesn't make sense. If, say, you find an NPN transistor with 6V on the base and 2V on the emitter, it's obviously blown.

If you find a transistor or IC pin where signal disappears, check to make sure the pin is soldered correctly to the PC board. If an IC is in a socket, the connection may be bad – some years ago a major socket manufacturer made a large run of sockets that have been giving trouble – or the solder joint between socket and PC board may be bad. Check the signal on the board, and also directly on the IC pin.



Also check the other end of the system: is the signal reaching the load? If not, is the load disconnected, or the cable shorted? Or, if the system is working but not working right, is the load blown, and the unit feeding its signal into an open circuit? Maybe the signal goes several places – is one of those places disconnected or shorted? Improperly terminated cables are a frequent source of data errors.

When servicing equipment at the component level, your best friends are Ohm's Law and a deep knowledge of semiconductor operation. Often, the malfunction prevents you from turning the power on, so you have to try to find the problem with an ohmmeter.

SIGNAL SUBSTITUTION

It's often useful to replace the actual signal with a calibrated signal from a signal generator. Video, for example, is such a complicated signal that there's no way you can adjust a system using an actual picture off the air, so you use a video pattern generator.

This also helps isolate the problem – if the system works properly with the signal generator, then the incoming signal is bad and you have to look at the antenna, cable etc.

Often, circuit diagrams will show proper waveforms at various points in the circuit. You need a signal generator to make use of these illustrations, because they're only valid with a specified input signal. If you find a place where the waveform is missing or distorted, you are downstream from the fault. Trace backwards until you find a place where the waveform is correct. In between, you'll find the problem.

In digital equipment, an **injector** with a square wave output can be used to test individual gates and data paths.

REPLACING COMPONENTS

You've found the problem, time to fix it. In many cases, you'll just swap a good unit or PC card for a bad one. If you solder and unsolder components, and any of them are CMOS, observe proper ESD (electrostatic discharge) precautions. The soldering iron should be Earth-grounded. You should be Earth-grounded via a wrist strap with a 1Meg resistor in series between you and ground. The bench top should be metal, or have a metal pad on it, Earth-grounded through a 1Meg resistor. I will assume you were paying attention during chapter 1 and you know how to solder.

If you remove a power transistor or similar device with heat sink grease under it, you need to wipe off the residue and apply new grease. Very likely, the original grease dried out and that is the reason the component failed in the first place. The only acceptable kind of grease is the stuff you get from electronic parts stores, made for purpose. Since every Radio Shack has it, there is no excuse for using gearbox grease or something else that's the wrong stuff.

When possible, use identical parts. Where you can't get an original part, use a replacement cross-reference book. NTE is one major source of replacement parts. (Google NTE01.) In a large percentage of cases, these precautions are not strictly necessary. There are many circuits where any old NPN transistor will work. But if you substitute that way, you better be very sure of your understanding of circuit operation. With life-safety equipment, always use identical parts, not because other parts won't work, but because lawyers will seize on any chance to make a jury think you've been negligent.

TESTING

Once the unit has been repaired, don't just turn it on, run it for a few seconds and say it's okay. Check to see that it's operating *correctly* – that the levels and gains are right, etc. When a component goes bad, it often stresses other components and they change their values. Or, the malfunction may have been caused by a problem in some other part of the circuit that you have not yet identified. Run the unit for a couple of hours to be sure it won't croak as soon as it's put back in operation. While it's connected and running, bang it on the benchtop (not too hard!) to be sure there are no loose connections.

FINISHING UP

You are not finished when the unit works. As boring as it may be, you must fill out all the paperwork right away, before you forget things. Put parts and tools away and clean up your workspace. *Then* you're finished.

One of the benefits of doing paperwork right away is that when you do it as part of a job, you can include the time it takes in your billing. This improves your productivity, as discussed above.

THAT'S ALL, FOLKS!

And just like that, wow, here we are at the end of the EM5 study guides. I suppose I should think of something important-sounding to say, but after all this writing, it's too much work.

There have been times when writing these study guides has seemed like a never-ending project, and it feels a little strange to finally be at the finish line. There's an EM6, but as of 2-2014 I'm not sure there's going to be an EM6 study guide. I agreed to do five. We'll see. Dunno what I'm going to do now. Maybe take up belly dancing. (Yow. I'm old, fat and wrinkly, and I have surgery scars. Bad image.)

I'm certainly going to celebrate. You should too, because if you've gone through all five and you're taking the EM5 exams in sequence, you'll also qualify for a CETa now. From there you can move on to earning a journeyman certification in a specialty area of electronics. If you're really ambitious, you can earn half a dozen varied journeyman certs and then you'll be a CETma, a master-level certified electronic tech. We hear from working techs, out in the field, that even if you have a college degree it pays to have additional certifications.

Before I turn you loose, I have to stick something in your head for future reference. Years down the road, when you've got a good job and lots of experience, it will be your turn to introduce younger people to electronics. Maybe you'll use these study guides. (Please be sure the per-student fee is paid to ETA, I get my cut from that.) We need all the skilled techs we can get. And there are big psychic rewards when you help younger people learn this stuff, and watch as the light bulbs go on. I should know.

Thanks, hey. If I can think I played a part in setting you up for a successful career, that will be the best present anybody ever gave me.

End of Chapter 10

CHAPTER 11 – EM5 REVIEW

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CHAPTER 1 - SOLDERING

FUSING – solder joins two conductors by dissolving a little of each, forming one piece with chemical composition that changes slightly from one area to the next.

TIN/LEAD ALLOY – traditional solder is a mix of tin and lead, which melts at a lower temperature than either tin or lead alone. Excess solder should be treated as hazardous waste.

EUTECTIC SOLDER – the tin/lead alloy that melts at the lowest temperature. It's 63% tin and 37% lead, and it melts at 361.4°F.

STANDARD ELECTRONIC SOLDER – 60% tin, 40% lead. It's a bit cheaper because tin is much more expensive than lead. It is solid below 361°F, mushy between 361 and 374°F, and liquid above 374°F.

LEAD-FREE SOLDER – mostly tin, a little silver and usually copper. Melts at about 420°F. Tin, lead, tin/lead eutectic, and lead-free solder go directly from liquid to solid with no mushy range.

TINNING – coating a conductor with a thin layer of tin or solder to make soldering easier and prevent oxidation.

THE FOUR Ts OF SOLDERING – especially important with lead-free solder.

- The right **tip**
- **Tinning** the tip
- The right **temperature**
- The right **timing**

FLUX – a material applied to the joint which melts during soldering and removes oxide. Only “rosin” flux (actual tree sap, or its functional equivalent) is acceptable. Acid core solder must never be used in electronics.

FLUX CORE – solder in the form of a tube, filled with flux

FLUX REMOVER – usually a solvent spray, dissolves flux left on a joint after soldering.

WATER-SOLUBLE FLUX – flux that can be washed away with water.

NO-CLEAN FLUX – flux that usually doesn't need to be washed away, but in cases where it does, is hard to remove.

SOLDERING IRON – a tool which runs continuously, with a replaceable tip. Tips are available in various sizes and shapes, in plain copper or with an iron plating.

PITTING – a non-plated tip will develop pits during use, due to the fact that the solder is gradually dissolving the copper.

HOLDER – a place to put the soldering iron when you're not holding it, to keep it away from things that may be burned. The only acceptable kind of holder is one that completely surrounds the iron, and is bulky enough that it cannot easily be tipped over.

SPONGE – for wiping crud off the tip. Must be an organic sponge; a foam sponge would melt and stick to the iron. The sponge should be damp when using it. A good holder will include a tray to hold the sponge.

THERMALLY CONTROLLED IRON – an iron with an adjustment that lets a user set temperature. A good one will have an actual thermostat to keep the temperature constant under all use conditions

SOLDERING STATION – a thermally controlled iron with a large base that also serves as a holder and a place for the sponge, and usually has a readout that shows temperature.

SOLDERING GUN – as opposed to an iron, a device which only runs when you're pulling the trigger. Most guns use high current to heat the tip. Heavy and crude, the main advantage is that the tip cools down quickly after releasing the trigger.

WETTING – spreading molten solder on the joint. Every part of the joint should be wetted; i.e. all surfaces should wind up covered in solder.

SWEATING – heavily pre-tinning all parts of a joint, then applying heat and melting them all together, without adding more solder.

COLD SOLDER JOINT – a joint where solder has not properly wetted one or more of the parts, so alloying did not happen, or a joint that has been flexed while cooling.

HEAT SINK – a device that is clamped onto a clip lead during soldering to keep excessive heat from reaching the component.

SILVER SOLDER – solder with silver in it, used to avoid damaging silver terminals which are found in some expensive equipment. No-lead solder usually has silver in it.

PHOSPHOR-BRONZE – a metal popular for switch contacts because it is hard to bend out of shape. Can be soldered, but the joint is not very strong, the circuit must be arranged so as not to put stress on the joint. Redish-colored.

MOST COMMON REASONS FOR A BAD SOLDER JOINT

- Unclean or oxide-coated surfaces (Rosin, being a gentle, non-corrosive chemical, cannot remove heavy oxide.)
- Insufficient heat for an insufficient time.
- Failure to heat all parts of the joint at once
- Movement while solder is cooling
- Trying to solder metals like aluminum that cannot be soldered by usual methods

SURFACE-MOUNT COMPONENTS – usually soldered by first applying a solder-bearing paste to the PC board pads, placing the part on the board, then using hot air to melt the paste.

DESOLDERING – removing solder from a joint so a part can be removed. Three methods:

- Melt the solder, then whack the board, letting momentum remove most of the solder.
- Melt the solder, then apply a vacuum device.
- Apply solder wick, then apply the iron. Heat moves through the wick to melt the solder.

VIA – a connection between a trace on one side of a PC board to a trace on the other side, or in complex boards, to traces buried inside. The connection is made by depositing a metal plating on the inside of a hole during manufacture. On a dual- or multilayer board, a through-hole connection to a component is essentially a large via with a component lead stuck into it and soldered.

CHIP DESOLDERER – a large soldering-iron tip that can heat up all the leads of an IC at the same time.

SOLVENT DISPENSER – flammable solvents should never be on your workbench while an iron is hot, but when you can't avoid it, the solvent should be in a dispenser that limits how much can catch fire at a time.

CHAPTER 2 – WIREs & INSULATION

RESISTIVITY - the characteristic resistance of a conductor. Resistivity is specified for a chunk of the material having one meter of area and one meter of length, e.g. a 1-meter cube.

The symbol for resistivity is **ρ.**

Most wires are copper. The resistivity of copper is 1.7×10^{-9} ohms per cubic meter. Silver is a little lower, 1.6×10^{-8} ohms, but is so much more expensive that it's only used in special cases. Aluminum is about 60% higher, 2.7×10^{-8} ohms, so it's not as good a conductor, but it's so much lighter and cheaper than copper that it's preferred for long-distance power transmission.

RESISTANCE VS. LENGTH – a wire's resistance is proportional to its length. Double the length, double the resistance. That is, every foot of wire has the same resistance as every other foot, so resistance depends on how many feet.

RESISTANCE VS. AREA – a wire's resistance is inversely proportional to its area. Double the area, cut the resistance in half.

RESISTANCE VS. DIAMETER – a circle's area is proportional to the square of its diameter, so if you double the diameter, you quadruple the area and cut resistance by ¾.

RESISTANCE VS. TEMPERATURE – resistance rises as temperature rises. For copper, over a limited range, the relationship is fairly linear. Resistance rises about 0.4% per degree C or 0.22% per degree F.

VOLTAGE DROP – loss of voltage from one end of a wire to the other, due to wire resistance. For DC and low-frequency AC, this is a simple Ohm's Law calculation:
drop = current X resistance.

POWER LOSS – power burned up in the wire. For DC and low-frequency AC:
power loss = voltage drop x current. Measured in watts.

POWER LOSS VS. LENGTH – power loss is proportional to length, since every foot burns up as much power as every other foot.

POWER LOSS VS. AREA – power loss is inversely proportional to area.

POWER LOSS VS. DIAMETER – power loss is is inversely proportional to the square of diameter.

POWER LOSS VS. VOLTAGE – for a given number of watts delivered to the load via a given wire, power loss is inversely proportional to the square of voltage. Raising the voltage makes it possible to lower the curent, which then lowers voltage drop. Since power loss is voltage drop times current, the effect multiplies.

WIRE GAUGE – the standard way of measuring wire diameter is in AWG or American Wire Gauge. Larger numbers indicate smaller wire. 40-gauge wire has one ohm of resistance per foot. Every 10 gauges larger, resistance falls to 10% of the previous value; e.g. 30, 20 and 10 gauge wire have resistances of 0.1, 0.01 and 0.001 ohm per foot.

Above 0 gauge, zeroes are added up to 0000 gauge (alternately called 4/0 gauge).

CIRCULAR MIL – the method used to label very large wires. A circular mil is the area of a round wire 1 mil in diameter, which is actually about 8×10^{-7} square inch. A large wire would be so many thousands of equivalent circular mills, as in 250kcmil (equivalent to 250,000 1-mil wires). Also written 250MCM.

A 1-mil wire conveniently happens to have about 10Ω of resistance per foot. The per-foot resistance of, say, a 250kcmil wire is simply 10Ω divided by 250,000, or 0.00004Ω.

MAXIMUM CURRENT – the max current a wire can carry depends on two factors:

- how much voltage drop or power loss is acceptable
- how hot the wire will get

Heating is a complicated issue, because temperature rise depends not only on how much heat the wire is creating but how fast it is being dissipated, and that depends on whether it's in the open or enclosed, surrounded by padding etc. It also depens on the wire's insulation, because different materials melt at different temperatures, and some can catch fire. Where building wiring is concerned, there's a rule: 14ga. wire is good to 15 amps, 12ga. wire is good to 20 amps, 10ga. wire is good to 30 amps.

DUCTILITY – how much a wire can bend without breaking.

FATIGUE – when a wire is bent back and forth a lot, the wire will break at that point. This is called wire fatigue.

SOLID WIRE – a conductor that's in one cylindrical piece.

STRANDED WIRE – a conductor made up of many smaller-diameter conductors. Stranded wire is much more resistant to fatigue, and is usually required by the Code when connecting to things like motors that vibrate.

TINNED WIRE – either stranded or solid, a wire that is coated with a thin layer of tin. This slows oxidation and makes soldering easier.

COLD CREEP – aluminum wire has two problems. One, it cannot normally be soldered. Two, it is so ductile (has such great ductility) that connections tend to loosen. This requires special connectors and special training to deal with.

INSULATION – an insulating material covering a wire, so it can touch other things without making electrical contact with them. Connection is made by **stripping** a short length of insulation off each end.

VARNISH – a hard insulating coating once made of actual varnish, now made of **formvar** or a similar plastic.

JACKET – a soft rubber or plastic insulating tube surrounding the wire. Common types:

- Rubber – used for wires that will be flexed a lot
- PVC – a common inexpensive jacket, not flame resistant
- PTFE (Teflon®) - fireproof, melt-resistant, often stiff and hard to use
- Cloth – used for appliance cords because it does not melt. Usually, a cloth braid over rubber-jacketed conductors.
- Glass fiber – used in very high temperature applications

FIRE RATINGS – how a given type of insulation behaves in terms of supporting fire or giving off noxious gasses in a fire.

- no designation – can be freely used in public buildings except as noted below.
- R - “riser” wire, must be used for vertical runs between floors to prevent fire from being spread from one floor to the next.
- P - “plenum” wire, for use in air ducts and the like. Plenum-rated insulation, such as PTFE, does not burn, does not support fire, and does not emit noxious gases.
- X – has no fire resistance; use in public buildings is very restricted.

PLENUM – the space above a ceiling, when it is used as an air conduit.

SKIN EFFECT – the tendency of alternating current to move away from the center of a wire and toward its surface, resulting in concentrated current near the surface and little current in the center. Skin effect is proportional to frequency. DC has no skin effect.

SKIN DEPTH – a somewhat arbitrary figure, the distance into a wire where current falls to 63% of its surface value.

LITZ WIRE – stranded wire where every strand is coated with varnish. Used to minimize skin effect.

WAVEGUIDE – a tube, usually rectangular, used to convey very high radio-frequency waves as wire would convey lower-frequency and DC energy.

INDUCTANCE AND CAPACITANCE – a single wire has inductance, and two nearby wires have capacitance between them. This is important at very high frequencies, at high impedances, and with long runs. Calculation of these values is complicated and beyond the scope of this study guide.

CABLE – two or more wires in a single jacket or twisted together, intended to be used as a unit.

BUNDLING – joining wires with cable ties or lacing to create a cable.

COAXIAL CABLE - "coax," a cable where one wire is inside the other. The outer wire acts as an electrostatic shield and the fact that the wires are located on the same axis causes the magnetic field to be contained, equivalent to an electromagnetic shield.

ZIP CORD – a cable with two or three wires in a jacket. The jacket has deep grooves between wires to enable it to be torn or "zipped" apart, so each wire can be connected to its own terminal.

RIBBON CABLE – zip cord with many conductors, designed to be terminated by **mass-termination** connectors which do not require stripping the insulation.

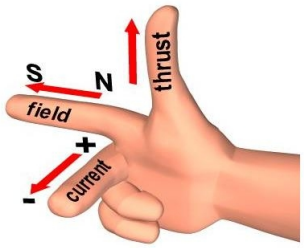
UTP – unshielded twisted pair, which relies on a balanced signal to prevent crosstalk and reject interference.

STP – shielded twisted pair, UTP plus a shield for extra protection. The shield must be connected to the chassis of the same units the pair is connected to, or it does no good.

CHAPTER 3 – GENERATORS

ELECTROMAGNETIC INDUCTION – voltage induced in a wire when it moves through a magnetic field, a field moves past it, or it sits in a field whose intensity is changing. For a moving wire or field, the wire must be positioned across the lines of force, so they "cut through" it.

FLEMING'S RULES – rules which show how the direction of magnetic flux lines, the direction of wire motion, and the polarity of voltage induced in the wire are related.



RIGHT HAND RULE FOR GENERATORS – used by those who think in terms of conventional current, flowing plus to minus.

LEFT HAND RULE FOR GENERATORS – used by those who think in terms of electron flow, minus to plus.

GENERATOR – a device which uses magnetism to convert motion to electricity. There are other electricity-generating devices but they are not usually called "generators."

PRIME MOVER – the source of energy in a generating system, e.g. coal, water, wind

AC GENERATOR – all generators are AC.

DC GENERATOR – made by taking the output of an AC generator and switching it back and forth so current always flows in the same direction.

ROTOR – the rotating part of a generator.

STATOR – the stationary part of a generator.

SLIP RINGS – used to make contact to he coil in a spinning rotor.

COMMUTATOR – in a DC generator, split slip rings that also perform the current-steering function to turn AC into DC.

ARMATURE – the part of a generator where the output voltage is created. This will have one or more coils of wire.

FIELD – the part of a generator that creates a permanent field that induces voltage in the armature coils. The field may be permanent magnets, or it may be an electromagnet, driven by direct current.

In small generators, the rotor is usually the armature. In very large generators, the stator is usually the armature.

EXCITATION – magnetizing the field by running DC through its coil. In a DC generator, some of its own output can be used to excite the field. This can also be done with an AC generator if some of its output is fed through a rectifier.

POLES – the number of magnetic poles in a rotor or stator. The minumum is two, one each North and South.

SERIES-WOUND – a generator where field and armature windings are connected in series. Output voltage is unstable.

PARALLEL- WOUND – a generator where field and armature windings are connected in parallel. Output voltage is fairly stable but tends to sag when the load is increased.

COMPOUND-WOUND – mostly parallel wound, with just enough of a series winding to counteract voltage sag. The generator design with the most stable output voltage without electronic control circuitry.

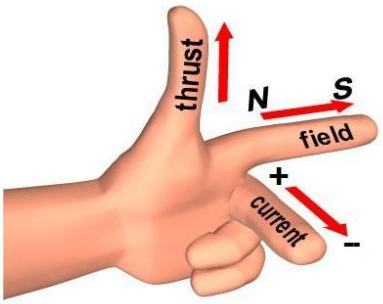
THREE PHASE GENERATOR – an AC generator that puts out three sine waves spaced 120 degrees apart.

WYE CONNECTION – a 3-phase wiring method where one end of each coil is joined at a common point. This point is typically grounded. The diagram resembles the letter “Y.”

DELTA CONNECTION – a e-phase wiring method where each coil is connected across two output phases, with no common junction. The diagram represents a Greek letter Delta.

ALTERNATOR – another word for AC generator. Oddly enough, usually refers to an automotive generator, which includes rectifiers to turn AC to DC.

CHAPTER 4 – MOTORS



LEFT HAND RULE – for conventional current, the generator rule is right-hand and the motor rule is left-hand.

RIGHT HAND RULE – for electron flow, the generator rule is left-hand and the motor rule is right-hand.

SERIES-WOUND – a DC motor with armature and field coils wired in series. Though series generators are little used, series motors are very popular. They produce more torque in a smaller size than any other type. There is no built-in speed limiting function; without a load (even if only its own friction), a series motor will spin up until it destroys itself. For this reason, series motors usually are permanently attached to a load, e.g. a hand drill.

SHUNT-WOUND – a DC motor equivalent to a parallel-wound generator, with field and armature coils wound in parallel. Reasonably stable speed.

PERMANENT MAGNET – a DC motor where the field is supplied by permanent magnets. Unlike a series motor, this motor has a speed limiting function due to the back-EMF created by the armature. If the motor is made to rotate too fast, it will actually apply a braking force.

SPEED CONTROL IN A DC MOTOR – can be done by varying the voltage.

DC MOTOR BRAKING – done by disconnecting the motor from the voltage source and shorting its leads.

UNIVERSAL MOTOR – a motor, usually seeries-wound, designed to work equally well on DC or AC. An example would be the series-wound motor in a kitchen mixer.

3-PHASE AC MOTOR – originally, a motor with a permanent magnet or electromagnet rotor and three field windings spaced 120° apart, connected to three sine waves. Though the stator does not move, its field rotates, pulling the rotor along with it.

SYNCHRONOUS MOTOR – an AC motor whose rotor speed is exactly the same as the speed of the rotating field.

INDUCTION MOTOR – an AC motor where the rotor is magnetized by induction from the field. This kind of motor requires no winding on the rotor and no commutator or slip rings. Its rotation speed is slightly less than synchronous; e.g. where a synchronous motor would be 1,800 RPM, an induction motor would by 1,750 at full load. The difference is known as **slip**.

SQUIRREL CAGE – a common way of making an induction rotor, consisting of copper plates on each end, joined by copper ribs. This insures that speed any difference between the rotating field and the rotor will create maximum current flow and maximum torque.

SINGLE PHASE MOTOR – a synchronous or induction motor designed to operate on one electrical phase. The necessary rotating field is created within the motor. In some cases, once the motor is up to speed, the rotating field ceases, leaving a stationary field that grows, diminishes and reverses along with the applied AC voltage. The motor depends on momentum to carry the rotor around so it lines up with the poles at the right moments.

SHADED POLE – a pole that is split, and part of it surrounded by a shorting ring, to shift its magnetic phase relative to the other part of the pole.

CAPACITOR-RUN – a type of motor where a capacitor is used to shift the phase to one of the two windings. A capacitor-run motor usually has low starting torque.

CAPACITOR-START – like a capacitor-run motor, but the capacitor is switched out of the circuit when the motor gets up to speed. A capacitor-start motor has large starting torque but usually has less running torque than a capacitor-run motor.

CAPACITOR-START-AND-RUN – a motor with two capacitors, one of which is switched out when the motor gets up to speed. Maximum start and maximum run torque.

SPLIT-PHASE – a motor that uses two coils of very different construction to create a phase difference.

2-POLE – the minumum number of poles in a motor, one each North and South. With 60Hz AC, a 2-pole synchronous motor spins at 3,600 RPM, an induction motor at maybe 5% less with full load.

For motors with more poles (always a multiple of 2), the synchronous speed is 7,200 |RPM divided by the number of poles.

MECHANICAL POWER – torque times speed. One mechanical horsepower is 550 foot-pounds per second of work. Electrically, one horsepower is 746 watts.

EFFICIENCY - actual 1HP motors put out less than 550 ft-lbs per second because the conversion from electrical power to mechanical power is not 100% efficient. Real-world efficiency varies from 95% or more for the very best, very largest motors to 70% or less for average motors in the 1HP range.

PULLOUT – most AC motors run at near-synchronous speed. If the load gets too great, they will pull out of near-synchronization, their torque actually declines, and they stall.

START & STALL CURRENT – a motor's starting current is typically 6X to 10X its running current. This does not damage the motor because it only lasts until the motor gets up to speed. If an excessive load should stall the motor, then it continuously draws this excessive current, which would quickly ruin the motor if the breaker didn't trip.

MULTI-TAP MOTOR – a motor whose windings are split so the user can choose which voltage to run the motor on, e.g. 120 or 240V.

SPEED CONTROL OF AC MOTORS – for most motors, the only practical method is to vary the frequency of the AC voltage. The voltage itself must also vary, so at lower frequencies the motor is fed a lower voltage and vice versa.

VFD – variable frequency drive, a relatively new technology that converts 60Hz power to some other frequency for the purpose of motor speed control.

DYNAMIC BRAKING – done by disconnecting an AC motor from its driving voltage and connecting it across a fairly low DC voltage. The advantage is that this kind of braking doesn't involve pads that can wear out or go out of adjustment.

BRUSHLESS DC MOTOR – a motor that uses transistors to perform the switching function traditionally performed by a commutator.

STEPPER MOTOR – a motor that rotates in discrete steps. Its main advantage is that it can stop and hold at a given position.

MICROSTEPPING – partially energizing some coils in a stepper motor to obtain positions between normal steps.

LINEAR MOTOR – a motor whose motion is back and forth instead of rotational.

REVERSING ROTATION – most DC motors can be reversed by reversing the polarity of the driving voltage. AC motors are reversed by changing the connections to some of the coils and capacitors, or in a 3-phase motor, reversing any two of the wires. In all cases you need to make sure the motor and the machine it's connected to are designed so it won't be damaged by reverse rotation.

CHAPTER 5 – THE AC POWER GRID

GRID – the system of generators and transmission lines. America has three grids, which interconnect to a limited extent: East/central, West, and Texas.

SMART GRID – the future of our grid, which will use electronics to control power generation and usage right down to individual refrigerators and air conditioners. The purpose is to use the expensive resources of the grid more efficiently.

LENGTH VS. POWER LOSS RULE – power loss in a transmission line is proportional to length.

VOLTAGE VS. POWER LOSS RULE – for a given conductor size, power loss is proportional to voltage squared.

AREA VS. VOLTAGE RULE – for a given amount of power loss, required cross-sectional area of the wire is propoertional to voltage squared.

DIAMETER VS. VOLTAGE RULE – for a given amount of power loss, required wire diameter is inversely proportional to voltage.

LENGTH VS. POWER LOSS RULE – for a given wire size and power loss, maximum length is proportional to voltage squared.

MOGEN – a coupled motor and generator, used to change voltage in a DC system.

TRANSFORMER – two coupled windings and a core, used to change voltage in an AC system.

DELTA AND WYE VOLTAGES – in a 3-phase system, voltages between phases are higher than from any phase to the common wye junction. To convert phase-to-phase to a phase-to-common measurement, multiply by 0.58. To convert phase-to-ground to phase-to-phase, multiply by 1.7.

UHV – ultra-high voltage, 100s of kV, used by long-distance power transmission lines.

ACSR – aluminum conductor, steel reinforced. The type of wire most use for UHV lines. Consists of a number of strands of steel in the middle for strength, surrounded by aluminum strands that carry the current.

PRIMARY TRANSMISSION – the main UHV long distance lines between a power plant and city. Almost always 3-phase, often 2 or more wires per phase to reduce skin effect. Some systems are DC. These do not have skin effect problems but may use multiple wires for practical reasons. 425kV is common.

SECONDARY TRANSMISSION – a lower voltage, typically 33kV, suitable for transmission over a part of a city.

PRIMARY DISTRIBUTION – distribution in a local area like a neighborhood, typically 12kV delta / 7.2kV wye.

SECONDARY DISTRIBUTION – the power feed to individual users, typically 120 / 240V for a home.

STEP DOWN – reducing voltage from a higher voltage to a lower voltage via a transformer.

SUBSTATION – a transformer installation to step down from primary to secondary transmission or secondary transmission to primary distribution voltage.

SUBSCRIBER TRANSFORMER – steps secondary transmission voltage down to secondary distribution voltage. A transformer on a pole is informally known as a pole pig.

POWER DROPS – wires connecting a subscriber transformer to the home or business it powers.

2-PHASE – incorrectly refers to 120 / 240V home wiring, actually single-phase, dual polarity. Since real 90-degree 2-phase systems are very rare nowadays, there's probably no harm in calling this 2-phase, and that's what people understand.

DIRECT BURIAL – long used for 120V, now used even for 12kV. Direct burial cable must have very reliable insulation and be water and rodent-proof.

BREAKER PANEL – the box where 120V power enters a building, usually including breakers for all **branch circuits** and a main breaker that turns all power off. The box is designed so alternating breakers are connected to alternate polarities. That way, a dual **ganged** breaker can be used for a 240V load.

FLOATING COMMON – occurs when there is a break in a (white) wire that is common to more than one branch circuit. This can cause gross voltage errors on the branch power lines.

TRANSIENT – a short-duration voltage spike far higher than the normal voltage on a wire.

MOV – metal oxide varistor, which provides a voltage clamping action to limit transients.

BASE LOAD – the expected electrical load on a generating plant during a certain time of day.

PEAK LOAD – a short-duration (e.g. a few minutes) load that exceeds the base load.

SPINNING RESERVE – the amount of power a generator is ready to deliver in excess of the base load. Large generators cannot be started or stopped quickly, so the generator must already be turning when the peak comes along.

PEAK SHAVING, LOAD SHIFTING, VALLEY FILLING – encouraging users to shift loads from periods of peak use, say 6PM, to periods of lower use, say 3AM.

POWER FACTOR – apparent power divided by real power, taking into account the phase difference between voltage across a load and current through it. A perfect power factor, where voltage and current are in phase, would be 1. A poor factor would be, say, 0.56.

Power factor is measured in **volt-amps**, which is not quite the same thing as watts.

REACTANCE – inductive and capacitive reactance (usually inductive) is what shifts the voltage / current phase relationship away from a perfect 0 degrees. Motors can imitate reactance depending on their construction and how they are loaded.

RENEWABLE ENERGY – energy that does not come from fossil fuels which, once used up, are not replaceable.

HYDROELECTRIC POWER – power generated by rivers and dams. Of all renewable power sources, it's the only one whose supply is reasonably predictable.

WIND AND SOLAR – increasingly practical, but these sources are unpredictable in the short term. They work best when they power loads that can be turned off for significant periods.

MICROGENERATION – power generation that's distributed among users, generation that occurs where the power is used, e.g. solar panels on a house.

CHAPTER 6 – CIRCUIT CONTROLS AND PROTECTION

SWITCH – used to make & break a circuit. A switch will typically have a maximum voltage rating, and several maximum current ratings for various conditions. A switch intended to control a motor may have a maximum horsepower rating.

GANGED or MULTIPOLE SWITCH – a switch with two or more **poles** that operate at the same time. In a schematic diagram, ganging is shown by a dashed line that indicates the poles are connected mechanically but insulated electrically.

POSITIONS – a switch has at least two positions, but may have many more. **Throw** means active positions, i.e. positions where a connection is made. In a single-pole single-throw (SPST) switch, only one of the two positions makes a connection.

KNIFE SWITCH – uses a swinging metal bar that shorts across two contacts when closed.

SLIDE SWITCH – uses a sliding metal piece that shorts across contacts when closed. Slide switches are inexpensive but they can arc if carrying high current. They are best used in **dry** circuits; that is, circuits which do not carry significant current.

SNAP SWITCH – a switch with a spring mechanism that prevents it from being opened or closed slowly. The purpose is to prevent arcs. Should always be used hin high-current circuits.

ROTARY SWITCH – essentially a circular slide switch.

MOMENTARY SWITCH – a switch that, if moved to a second position, will snap back the first position when released. An example would be the open-close switch for a garage door.

PUSHBUTTON – can be momentary, as in a normally open or normally closed switch, or alternating action, as in a computer on-off switch.

DISCONNECT BOX – a box with a handle on the side, used to control high-current AC circuits. Disconnect boxes use knife switches, but there is a spring mechanism to insure that, when a circuit is broken, it breaks quickly. Thus these are essentially snap switches. A disconnect box also typically includes a fuse or fuses, and often thermal switches.

LOCKOUT – a switch that must be pulled to operate, or one with a cover that must be lifted. The purpose is to prevent accidental operation.

RELAY – a switch operated by an electromagnet. Used where a low-voltage or low-current circuit must control a high-voltage or high-current circuit, or where one kind of current must control another kind, e.g. DC controlling AC. Also used to allow one closure to control several closures, and to allow an electronic device like a computer to control closures.

SOLENOID – in common usage, the word means a coil with a **plunger** armature that is pulled inside the coil.

SOLID STATE RELAY – a circuit that uses transistors or thyristors to mimic mechanical relay operation.

FUSE – a short wire in an enclosure, which melts when too much current flows in a circuit. It is current, and only current, which blows a fuse. A fuse will have a voltage rating, but that's to tell you the highest voltage the fuse is designed to work with. It does not factor into the fuse's current rating. The rated current is the maximum current at which the fuse will *not* blow.

FAST, MEDIUM, SLOW BLOW – how long an overcurrent must exist for the fuse to blow. Electronic equipment typically uses fast-blow fuses. Motors use slow-blow fuses, to permit overcurrent long enough for them to get up to speed.

CLIP FUSE HOLDER – a holder with a contact on either end, which does not enclose the fuse. Used only inside equipment because of the shock danger.

CARTRIDGE FUSE HOLDER – mounted in a panel, totally encloses the fuse. When a fuse is used in a cartridge holder, its current rating is reduced to 75% of its normal value; e.g. a 6A fuse becomes a 4.5A fuse.

THERMAL FUSE – a fuse which blows when the temperature around it reaches a certain level.

BREAKER – has the same function as a fuse, but can be re-set and re-used. May be a **thermal** breaker, which takes some time to trip, a **magnetic** breaker, which can trip in a fraction of a 60Hz cycle, or a combination of thermal and magnetic.

AUTO-RESETTING BREAKER – a breaker that will self-reset soon after the overload is removed.

GANGED BREAKER – several breakers mechanically connected together, so if one trips they all trip. Typically used with 2- or 3-phase circuits.

GFI – ground fault interrupt breaker, a breaker that detects an imbalance in outgoing and return current, indicating that some current is flowing to ground.

ARC-SENSING BREAKER -- a breaker that looks for the type of waveform on the power wires that will be generated if arcing is present.

CURRENT-LIMITED SOURCE – a power source that has a built-in limiting function, so even if the wires are shorted, not enough current flows to be dangerous.

CHAPTER 7 – INTERFACING ELECTRONIC CIRCUITS: LEVELS & IMPEDANCES

IMPORTANT FACTORS – the four most important things you have to know are:

- What the signal source is like
- What the signal destination (whatever the signal is being fed to) is like
- What the transmission path is like
- What the signal itself is like

IMPEDANCE – the algebraic sum of resistance, capacitive reactance and inductive reactance, measured in Ohms.

TRANSMISSION LINE – a cable that's long enough to permit internal signal reflections at the ends. As a rule of thumb, a cable begins to show transmission line behavior when it's more than1/10 as long as the wavelength it's carrying.

CHARACTERISTIC LINE IMPEDANCE – the impedance of a transmission line.

WAVELENGTH – the length of a single cycle of a certain frequency as it moves through space or through a cable, measured from the beginning of one wave to the beginning of the next. In space, wavelength is 3 x 10^8 meters divided by frequency. In a cable it's somewhat shorter because signal moves more slowly through a cable. The formula is l=S/F, wavelength = speed / frequency. The speed of an electrical wave in air or space is about 3 x 10 meters per second.

TYPICAL CABLE IMPEDANCES – coaxial cable intended for radio frequencies is almost always 50W. The exception is cable intended for video signals, which is 75Ω. Flat twinlead cable, as used by FM antennas, is 300Ω. Twinax, which is twinlead in a shield, is 100Ω. CAT5 and similar data cables are usually 100Ω. For audio cables, unless they are very long (e.g. a mile), impedance doesn't matter much because the wavelengths are so long most audio cables are not transmission lines.

IMPEDANCE MATCHING – where transmission lines are involved, the cable, the unit sending the signal into the cable, and the unit receiving signal from the cable must all be the same impedance. Otherwise, part of the signal will be reflected at the junction points. This reduces transmission efficiency and can lead to data errors. The exception is again audio, in which impedances are only matched where cables are very long, e.g. the telephone system. Otherwise, in audio, the sending unit tends to have a very low output impedance and the receiving unit tends to have a high impedance.

BALANCED, UNBALANCED – a balanced signal requires two wires; the signal appears as a differential voltage or current across the wires. An unbalanced signal requires one wire and a ground reference; the signal appears as a voltage on the wire, measured against ground. Unbalanced signals have the advantage of simplicity and low cost. Balanced signals have the advantage that they are almost immune to received interference, and radiate almost no signal to interfere with other things.

IMPEDANCE CONVERSION - where equipment of unequal impedances must be connected together, an impedance conversion is performed. The most-used converter is the transformer. In many cases, a conversion between balanced and unbalanced signal is also performed. The transformer that does this is called a **balun**, for balanced-to-unbalanced (or vice versa).

GROUND – a reference point that is defined as "zero volts." Inside a piece of equipment, all signals are measured against this reference. In a system with many pieces of equipment, problems can arise because different ground references may not actually be at the same voltage. A tech should develop the ability to visualize what's going on with the grounding scheme and where voltage differences could arise.

SIGNAL LEVELS – analog signals, and digital signals under some conditions, may be measured in terms of volts, amps, watts or decibels depending on the specific type of signal. You already know about volts, amps and watts, but few are comfortable working with decibels. This is something a tech should know, so here's a fairly detailed summary. If you get to the end of this summary and still are shaky, go back and reread chapter 7.

DECIBEL – abbreviated dB, a logarithmic (proportional) measurement of power or voltage or, rarely, current. Decibels permit us to conveniently label and compare a very wide range of levels.

Decibels are *comparative* measures. They tell us how much stronger or weaker one signal is than another signal. If signal B is stronger than signal A, the dB reading will be positive, e.g. +6dB. If signal B is weaker than signal A, it will be negative, e.g. -10dB. If they are the same, the difference will be 0dB.

dBs can also tell us how a certain signal has changed from a previous level. When a signal is boosted, the change is positive, e.g. +6dB. When a signal is attenuated, the change is negative, e.g. -10dB. When a signal comes out at the same level it went in, there is no change, i.e. 0dB.

When we're measuring power, 10dB corresponds to a 10:1 power ratio. +10dB means multiplying the power by 10X; -10dB means cutting power to $^{1}/_{10}$ its original level. We can do this more than once: +20dB means multiplying power by 10 and then 10 again, 10 x 10 = 100 times the original level. +30dB means 1,000X the original level and so on.

When we're measuring voltage, the numbers double: 10X the original voltage corresponds to +20dB. +10dB would be the square root of 10X the voltage, or about 3.2X. Most techs don't actually do these calculations, they memorize numbers. There's a dB chart at the end of this chapter that you can print out and keep in your notes.

Officially, the dB formulas are:

dB = 10log (P2/P1) for power, dB = 20log (V2/V1) for voltage.

dBs are comparative, but if we choose an absolute level and call it “0dB,” then we can use dBs to identify other absolute levels, in comparison to this 0dB reference. We add a letter after “dB” to identify the reference. Some common references:

- 0dBW 1 watt
- 0dBkW 1kW
- 0dBm 1mW (0.78V in a 600W circuit)
- 0dBV 1V
- 0dBmV 1mV
- 0dBu about 0.78V
- +4dBu about 1.23V

0dBu exists because it’s a modernized form of the old audio standard reference, 1mW (0dBm) in a 600W circuit. Telephone circuits are usually 600W, and pro audio circuits used to be 600W back when impedances were matched. (Old habits die hard.) The “full volume” level in professional audio is actually a little hotter, +4dBu, which is about 1.23V. That’s the level that reads “0” on a standard VU meter.

TYPES OF SIGNAL:

AUDIO – signals in the range of frequencies we can hear, roughly 20Hz to 20KHz. Audio signals are different from most other types because huge moment-to-moment variations in level are normal, e.g. 1mV in the quietest parts to 1V in the loudest.

LINE LEVEL – a good, practical level for routing and distributing audio signals, roughly corresponding to the levels you’d find on a telephone line. In professional work, the standard “full volume” line level is 1.23V and the circuit is balanced. In consumer equipment, it’s around 0.3V and the circuit is unbalanced. Generally, where you find a 3-pin XLR connector, you’re dealing with professional level, while an RCA (phono) connector indicates consumer level. A ¼ “ phone connector can be either.

In program material that varies widely in loudness, e.g. symphonic music, the quiestest parts may correspond to voltages that are 1/1000 of the maximum level. In moments of silence, of course, the voltage is essentially zero.

Since the sending unit and receiving unit are usually different impedances, it’s hard to identify a single impedance for an audio line. The sending end of pro equipment likes to see a load of 600Ω or greater. The sending end of consumer equipment likes to see a load of 2kΩ or greater.

MICROPHONE LEVEL – usually much lower than line level, except on the loudest sounds. A typical level for someone speaking 18” from a microphone would be 1-2mV. Professional mics have an impedance of 150 or 600Ω, and feed preamplifier inputs of much higher impedance, 2kΩ and up. A microphone circuit may also have up to +48V of **phantom** DC on it to power a condenser mic’s internal preamp.

SPEAKER LEVEL – voltage varies from line level to much higher than line level, depending on power. (Example: 100W into an 8Ω speaker corresponds to about 30V.) Impedance is very much lower and current is very much higher. Speaker signals are measured in watts, not volts. The most common speaker impedance is 8Ω. Actual amplifier output impedance is a tiny fraction of one ohm; that is, it's a stiff voltage source.

A special type of speaker system is used in large buildings, based on a maximum voltage rather than power level. The most used standard voltage is 70.7V. This is called "constant voltage," which can be very confusing because the voltage varies with loudness like any other audio signal. The voltage specification refers to the maximum voltage before clipping.

HEADPHONE LEVEL – about the same as consumer line level (0.3V) but much lower impedance (typically 32Ω) and higher current. Usually measured in watts; 30mW is very loud.

TELEPHONE – the wired telephone system is becoming obsolete, but it includes standards which all modern telephone equipment must meet for the sake of smooth operation. A POTS (plain old telephone service) line is a balanced or pseudo-balanced pair with one wire grounded and -48VDC on the other wire, which drops to about -5V when the line is in use. Audio is superimposed on this DC voltage, in the form of fluctuations that amount to about a volt of AC on very loud speech. A 90V, 20Hz sine wave is used to ring the bell.

For the tech, the most important thing about a phone line is that there can be no connection between the line and ground at the user end. A transformer must be inserted to isolate the line from local grounds, and sending or receiving impedance is 600 or 900 ohms (ask the phone co which).

HEADROOM – the difference between the maximum level as it would show up on a VU meter, and the maximum instantaneous voltage the system can handle, measured in dB. For example, if a system's clipping level is 12.3V, that's 20dB above 0VU, so the system has 20dB of headroom.

DYNAMIC RANGE – usually, the difference between loudest and quietest parts of an audio signal. More broadly, the range of level variation of any particular signal.

AVC – automatic volume control, a system that automatically adjusts gain to keep sound volume within desired limits; i.e. reducing the dynamic range.

AGC – automatic gain control, equivalent to AVC but not limited to audio. For example, a TV includes AGC to compensate for the difference between strong and weak signals.

COMPRESSION – using AGC to reduce the voltage variation of a signal.

EXPANSION – using AGC to increase the voltage variation of a signal. Most often used to reverse the effects of compression, restoring a signal's original dynamic range.

COMPANSION – matched compression and expansion. Dolby noise reduction is probably the most familiar example.

BASEBAND VIDEO – video as it comes out of the camera, with instantaneous voltage corresponding to instantaneous brightness. Voltage is typically about 1V peak to peak. This level must be maintained throughout the system – every part of the system must have a "gain" of 0dB – because if the signal gets larger or smaller, the picture will get brighter or darker.

ANALOG MODULATED VIDEO – baseband video impressed on an RF carrier, the way audio is impressed on a carrier in radio. Obsolete in broadcast, but still used in closed-circuit TV systems. In all analog video, whether baseband or modulated, the standard impedance is 75Ω. Voltage can be anything, meaning a TV must have a very capable AGC circuit.

DIGITAL MODULATED VIDEO – baseband video turned into a digital data stream. Since digital techniques and distribution are being used, the distribution system may conform to something other than the standard 75Ω video impedance.

RF CABLED SIGNALS – RF signals of all types are usually carried on coax cables with 50Ω impedance. The most common exception is TV and FM antennas, whose outputs are a balanced 300Ω. This can either be fed to the TV or FM radio as is, over twinlead, or transformed to 50Ω using a balun at the antenna.

RF RADIO SIGNALS – "radio" in this context means not only AM and FM, but any high-frequency signal transmitted over the air. Since transmitter power and distance between transmitter and receiver vary tremendously, a receiver must include an AGC circuit with a gain-control range of many orders of magnitude. Talking about the "impedance" of air and space gets complicated, and in any case it isn't the tech's concern. The important thing is that the transmitting antenna's impedance match the transmitter and the receiving antenna's impedance match the receiver.

DIGITAL LEVELS:
Voltages listed are at the sending end. Especially with higher-frequency standards like Firewire, there is considerable attenuation in longer cables. Some systems automatically detect and correct for level loss at the receiving end.

RS232 – unbalanced; "0" is officially +25V and "1" is officially -25V. Many RS232 systems don't get anywhere near these voltages, and may be as low as + and – 5V. The higher the voltage, the better the system's immunity to interference.

USB – balanced, a pair of wires that switch between ground and +3.3V. A USB bus also includes a +5V wire and a ground wire.

MIDI – unbalanced, optically isolated current loop, switches between 5mA and 0mA.

LVDS – unbalanced current loop, 3.5mA that reverses polarity to indicate "1" and "0."

ETHERNET – balanced, uses up to 5 voltage levels (1V, 0.5V, 0V, -0.5V, -1V).

FIREWIRE / IEEE1394 – balanced, two wires that sit at about 1.5V and vary from that by + or – 0.1V.

CAN BUS – balanced, two wires that are both +2.5V for "1." To indicate a "0," one wire goes to +3.5V and the other goes to +1.5V. A can bus also includes a ground wire and a +DC wire.

NOISE – something that interferes with the desired signal, whether actual random noise, some other signal, or interference created by, say, a light dimmer.

S/N – signal to noise ratio, the difference between signal level at a particular point and noise level at that point. Some signals, e.g. high quality audio, are ruined if there is just a little noise. Other signals can tolerate noise that's almost as strong as a signal. Once noise gets into a signal, it's usually impossible to remove it. If the S/N ratio goes negative (noise is stronger than signal), that usually means the signal is so degraded that it cannot be recovered.

There is always some noise in the environment. This dictates, among other things, how far a radio station will reach for a given transmitter power.

CHAPTER 8 – INTERFACING ELECTRONIC PRODUCTS: CABLES & CONNECTORS

IMPORTANT FACTORS

- Type of signal, including frequency
- Does the cable need to be shielded
- Does the cable need to be balanced
- Current and voltage requirements
- Characteristic impedance
- Signal loss per foot at the signal frequency
- Physical size

There are also mechanical factors, such as the need to be fireproof in some applications.

MULTI-STRIPPER, MILLER STRIPPER – insulation strippers with buit-in limits to avoid nicking the wire

HOT WIRE STRIPPER – used in critical applications where no wire nicking at all can be tolerated

WIRE WRAP – a solderless connection method where wire is wrapped around a post with sharp corners. The corners bite into the wire and keep it from slipping or loosening.

TINNING – coating the tip of a wire with solder. Usually not necessary, but in cases where it will be hard to apply solder during the soldering operation, both the wire and whatever it's being connected to should be heavily tinned first.

BRAIDED SHIELD – interwoven wires, which must be separated and pulled to one side for connection. If you need to bare more than ¾" of braid, it's better to pick a point and pull the wires apart with an awl, then pull the signal wire through the hole, rather than un-braiding the whole length. All the strands must be connected or soldered; you can't have any flyaway strands.

FOIL SHIELD – usually aluminum foil or aluminum-coated plastic. It's difficult to make a connection to this kind of shield, so foil-shielded cable has a bare drain wire that runs along the shield and makes contact with it; you terminate by connecting to the drain wire. Where there is a shield of any kind, it must be chassis-grounded to one or both of the units it is connected to. An ungrounded shield is useless or worse.

STRAIN RELIEF – if a cable will be flexed a lot, it should be tied down some distance from the connector so it doesn't flex at the connector, which is the weak point. If that is not possible, use a connector with a built-in flexible strain relief. BTW, a plug-mounted strain relief isn't much good at protecting against pulling or yanking. If that's going to happen, the cable must be tied down, or the system should be redesigned so the pulling and yanking doesn't happen.

DRIP LOOP – a loop in a cable to prevent water from running into the connector.

SPLICE – a connection made by twisting two wires together, without a connector, or with a wire nut or crimp cap, or using a crimp-type butt or telephone connector. The sturdiest type of wire-only connector is probably the Western Union splice.

PHONE CONNECTOR – a connector with a 1/4 " dia probe, divided into a tip, a sleeve, and in some cases a ring, to connect 2 or 3 circuits at a time. Originally used for telephone switchboards, now a mainstay of audio equipment.

PHONO CONNECTOR – also known as an RCA connector, a signal pin surrounded by a segmented grounding ring. Intended for audio but also used for composite video (yellow insert) and occasionally RF. An odd characteristic is that, when plugging in, the signal connector makes contact before the ground does. Because of this, it is recommended that the circuit be dead or gain controls turned down before making a connection.

XLR CONNECTOR – mostly used for audio, the most common type has 3 pins arranged in a triangle. Standard wiring has the pins pointing in the direction of signal flow; i.e. an input would be a jack and an output would be a plug. Intended for a balanced signal with pin 1 = ground, pin 2 = +, and pin 3 = -. Note that this is different from an AC outlet.

BANANA PLUG & JACK – a single-wire connector with an 1/8" diameter contact.

UHF / 259 CONNECTOR – essentially a shielded banana connector. The plug is a PL259 and the jack (socket) is an SO259. Called a "UHF" connector but standard ones are only good to about 150MHz. 50W, not used for video.

N CONNECTOR – a smaller connector with an inner shell (shield) that's separate from the screw-on part. 50 and 75 ohm versions are available, and usually not marked, so they are hard to tell apart. The 50W version is good to at least 10GHz.

BNC CONNECTOR – inner parts the same as an N connector, but the screw-on part is replaced by a bayonet arrangement for quick connect / disconnect. Most test equipment uses BNC connectors.

TNC CONNECTOR – a threaded (screw-on) connector like the N connector, but smaller overall size. The inner parts are the same as an N connector.

MOTOROLA CONNECTOR – used mainly in car radios, almost the entire plug goes inside the jack.

F CONNECTOR – a handy and inexpensive connector widely used in video systems. 75W.

D CONNECTOR – a D-shaped connector with 9 or more contacts. These can be solder-cup contacts permanently installed, or crimp contacts that are attached to the wires and then inserted into the connector body.

MOLEX CONNECTOR – a (usually) white rectangular plastic connector with high-current crimp-and-insert contacts, used a lot in cars. (Molex has become an almost-generic name for these connectors, but it's also a brand name.)

MODULAR / RJ CONNECTOR – an insulation displacement connector that does not require stripping the wire ends.

RIBBON CONNECTOR – an insulation displacement connector and wire system designed to permit fast connection of many wires. Mechanically very practical, its main drawback is the difficulty of preventing crosstalk between adjacent, unshielded wires. Used mainly in digital equipment where a small amount of crosstalk does not degrade the data the way it would in an analog system.

MIDI CONNECTOR – a standard-size DIN connector with 5 pins in a 180-degree arc. Pins 4 and 5 are used for the signal. Pin 3 may be connected to a shield, but MIDI will usually work without a shielded cable.

CRIMP LUG – for terminating a single wire. One end crimps onto the wire, the other end is an eye or spade shape to go under a screw head on a barrier strip.

PHOENIX CONNECTOR – a connector where a wire is inserted in a slot, then a screw is turned to clamp down on the wire.

CHAPTER 9 – MAKING MEASUREMENTS

MULTIMETER, VOM – a meter that makes several different kinds of measurements. Almost all VOMs (volt/ohmmeters) measure DC voltage, AC voltage, current, and resistance. Many also test diodes, measure transistor gain, and have an audible continuity function.

ANALOG VOM – shows readings via a needle-type meter. On voltage ranges, the meter loading (the resistance across the circuit being measured) changes when the range switch is changed. A typical value is 2kΩ per volt, meaning the resistance is 2k times the maximum voltage of the particular scale you're using. If you're on the 10V scale, the resistance is 2k x 10, or 20kΩ. Advantages of the analog VOM are that no power source is required (except for an internal battery when measuring resistance) and a needle-type indicator is easier to follow when the quantity being measured is changing.

DIGITAL VOM – shows readings via a number readout. On voltage measurements, meter loading does not change when the range is changed. Loading is typically 1MΩ or higher. Acvantages of the digital VOM are high accuracy and low loading. A digital VOM draws power, so it should be shut off when not in use. Many digital VOMS can only measure an AC voltage accurately up to a frequency of a few hundred Hz.

RANGE SWITCH – sets the voltage, current or resistance that represents a “maxiumum” reading on the meter. Similar to the zoom on a camera lens.

AUTORANGING – a convenience feature, the meter chooses the proper range for you.

ACCURACY – there will be a certain amount of error in any reading. General-purpose analog meters are usually accurate to 5%, digital meters 2% or better. AC voltage readings may be less accurate than other measurements. These are usually good enough, but if you need very high accuracy, you need a special meter, and maybe special measuring techniques.

RESOLUTION – in a digital meter, you can't see voltage increments smaller than the significance of the right-hand digit. For best resolution, set the range switch so the measurement fills up the available digits.

MEASURING VOLTAGE – the meter is connected across the voltage to be measured. If it's a high impedance circuit, you must remember to consider the effect that meter loading may have.

SPECIAL PRECAUTIONS WHEN MEASURING AN AC VOLTAGE:

- There's a diode in the circuit whose voltage drop may throw off low-voltage readings.
- Most meters only given an accurate reading with a 60Hz sine wave. Other waveforms or higher frequencies may not be measured accurately.
- If there's DC along with AC, the reading may be way off.
- If there's a capacitor in the circuit, the diode-like behavior of an analog meter may charge it up, giving a wrong reading
- If you need to measure non-sine waveforms, buy an RMS-measuring meter.

MEASURING CURRENT, DIRECT METHOD – the circuit is broken and the meter is connected across the break, so current flows through the meter. Care must be exercised; on some settings, some meters can be damaged by a current of 0.0001A.

MEASURING CURRENT, INDIRECT METHOD – the circuit is broken and a low-value resistor is connected across the break. The voltage drop across the resistor is then measured and current is calculated using Ohm's Law.

MEASURING RESISTANCE – the meter puts a small voltage across the circuit under test, then measures voltage drop. Power to the unit under test must be turned off so there is no source of voltage present except the meter's own voltage.

When measuring a part in-circuit, make sure none of the other things in that circuit are passing current and screwing up the reading. It is very often necessary to disconnect one end of a part from its circuit so it can be measured by itself.

MEASURING DIODE OPERATION – in diode mode, the red VOM lead is usually positive. Connecting a diode across the leads, with the anode to the red lead, should result in a reading of 0.6 to 0.7 (for a silcon diode), showing that current is flowing but there is a voltage drop. Connecting it the other way, anode to the black lead, should show no current flowing. A good diode must meet both conditions.

If a VOM does not have a diode setting, it can still test a diode. Set to a fairly low resistance range, like 2KΩ. With the red lead to the anode, the meter will show conduction, though the number displayed will not necessarily bear any relationship to voltage drop.

A few meters have reversed polarity – in resistance mode, the positive voltage is on the black lead. The firs time you use a meter, set it to a resistance range, then take another meter set to volts and verify its polarity.

MEASURING TRANSISTOR GAIN – the trick here is getting the right pin in the right socket hole; you have to be sure of the transistor's pinout (pin pattern). If you do this a lot, you'll get to where you know when you're getting a reading that doesn't make sense.

MEASURING CONTINUITY – the meter beeps when there's a current path. The first time you use a meter, connect a pot and find the resistance threshold where the meter starts to beep. Know your test equipment.

OSCILLOSCOPE – displays voltage plotted against time.

DUAL TRACE – an analog scope where the beam is switched back and forth to display two waveforms. If it's set properly, the traces will appear continuous. Since niether waveform is displayed continuously, the scope should usually be set to display a number of cycles, so something isn't missed. Digital scopes do not have this problem because all input signals are constantly being digitized, stored and recalled to the display.

PROBE – a special cable designed to get the signal from the unit under test into the scope without distorting the signal or upsetting circuit operation. Usually, there's a built-in switch to pre-attenuate the signal by 10:1 when desired. A typical probe presents a load of 1MΩ in parallel with a 30pf capacitor. Switching in the 10X attenuator reduces the loading to about 10MΩ and 3pf.

PROBE CALIBRATION – for a simple scope, the probe capacitance is adjusted until a square wave is displayed with square corners. This corresponds to a system frequency response that is flat out to the maximum frequency the scope is built to display. High speed scopes may require a more complicated calibration procedure.

VERTICAL RANGE SWITCH – serves the same function as the range switch on a VOM; adjusts the vertical gain so a signal of any voltage can be displayed at a reasonable size on the screen.

HORIZONTAL RANGE (SWEEP TIME) SWITCH – sets the time period displayed by a single scan across the screen.

TRIGGER – sets the start time of a sweep so a repeating waveform stays in one place on the screen.

FUNCTION GENERATOR – creates square, triangle and sine waves; may create sawtooth and rectangular (pulse) waves.

DUTY CYCLE – the positive alternation vs. negative alternation time relationship. A perfectly symmetrical wave, like square, sine and triangle waves, has a 50% duty cycle. Asymmetrical waves like rectangle and sawtooth waves, have a duty cycle greater or less than 50%. Some function generators allow the user to set the duty cycle.

SINE WAVE DISTORTION – in a simple function generator, the sine wave is produced by mashing the peaks of a triangle wave. A pure sine wave cannot be made this way; sine waves made by function generators typically have 1% or more distortion. Digital function generators may create the sine wave by reading values out of a look-up table. Waves generated this way can be very pure. Whether a particular shop needs the more expensive digital generator depends on what they use the sine wave for.

DC OFFSET – An AC wave may not average out to zero volts; there may be some DC in it too. Some function generators permit the user to set the overall DC level of the output; the AC wave appears as fluctuations above and below this average level.

MODULATION – a function generator usually has inputs that permit a waveform from another source to amplitude- and frequency-modulate its output.

TOLERANCE – the amount by which a part's actual value may differ from its stated value. Part values are not exact, and measurements are not exact. A tech must simply learn to accept this as reality, and always keep it in mind when making measurements and working on equipment.

CHARTS, GRAPHS, FORMULAS

AMERICAN WIRE GAUGE CHART

AWG	DIAMETER		RESISTANCE		AWG	DIAMETER		RESISTANCE	
	inch	mm	mili-ohm / ft	mili-ohm / M		inch	mm	mili-ohm / ft	mili-ohm / M
0000	0.46	11.7	0.049	0.16	20	0.032	0.81	10	33
000	0.41	10.4	0.062	0.20	21	0.029	0.72	13	42
00	0.36	9.3	0.078	0.26	22	0.025	0.64	16	53
0	0.32	8.3	0.1	0.352	23	0.023	0.57	20	67
1	0.29	7.3	0.12	0.41	24	0.020	0.51	26	84
2	0.03	6.5	0.16	0.51	25	0.018	0.46	32	110
3	0.23	5.8	0.20	0.65	26	0.016	0.41	41	130
4	0.20	5.2	0.25	0.82	27	0.014	0.36	51	170
5	0.18	4.6	0.31	1.0	28	0.013	0.32	65	210
6	0.16	4.1	.040	1.3	29	0.011	0.29	82	270
7	0.14	3.7	0.50	1.6	30	0.010	0.26	100	340
8	0.13	3.3	0.63	2.1	31	0.0089	0.23	130	430
9	0.114	2.9	0.79	2.6	32	0.0080	0.2	160	540
10	0.102	2.6	1	3.3	33	0.0071	0.18	210	680
11	0.091	2.3	1.3	4.1	34	0.0063	0.18	260	860
12	0.081	2.1	1.6	5.2	35	0.0056	0.14	330	1100
13	0.072	1.8	2	6.6	36	0.0050	0.13	420	1400
14	0.064	1.6	2.5	8.3	37	0.0054	0.11	520	1700
15	0.057	1.5	3.2	10	38	0.0040	0.11	660	2200
16	0.051	1.3	4	13	39	0.0035	0.09	830	2700
17	0.055	1.2	5.1	17	40	0.0031	0.08	1,000	3400
18	0.040	1.0	6.4	21	**Resistance is measured in mili-Ohms, thousandths of an Ohm per foot or per meter.**				
19	0.036	0.91	8.1	26					

Insulation ratings:

- X: lowest rating, acceptable use in public buildings is very limited
- (no rating): OK for most uses in public buildings
- R: must be used when a cable will go vertically from one floor to another
- P: highest rating, required when used in air-ventilation space, does not burn or emit noxious gases

Branch-circuit AC wiring gauges:

- 14ga: can be used in a circuit with a 15A breaker
- 12ga: can be used in a circuit with a 20A breaker
- 10ga: can be used in a circuit with a 30A breaker

Skin effect: skin depth is taken to be the depth at which current decreases to 63% of surface current. Skin depth is about **2.6 / square root of frequency**, measured in inches.

Fleming's rules for generators: right hand for conventional current, left hand for electron flow.

Fleming's rules for motors: left hand for conventional current, right hand for electron flow.

AC motor speed: 7200RPM / number of poles when AC frequency is 60Hz

Decibel power formula:

$$dB = 10 \log (P_2 / P_1)$$

- **1dB = 26% increase or decrease in power**
- **3dB = doubling or halving of power**
- **6dB = 4x or ¼x power**
- **10dB = 10x or $^1/_{10}$x power**

Decibel voltage formula:

$$dB = 20 \log (V2 / V1)$$

- **2dB = 26% increase or decrease in voltage**
- **3dB = 1.4 or 0.7 x voltage (square & root of 2)**
- **6dB = doubling or halving of voltage**
- **12dB = 4x or ¼x voltage**
- **20dB = 10x or $^1/_{10}$x voltage**

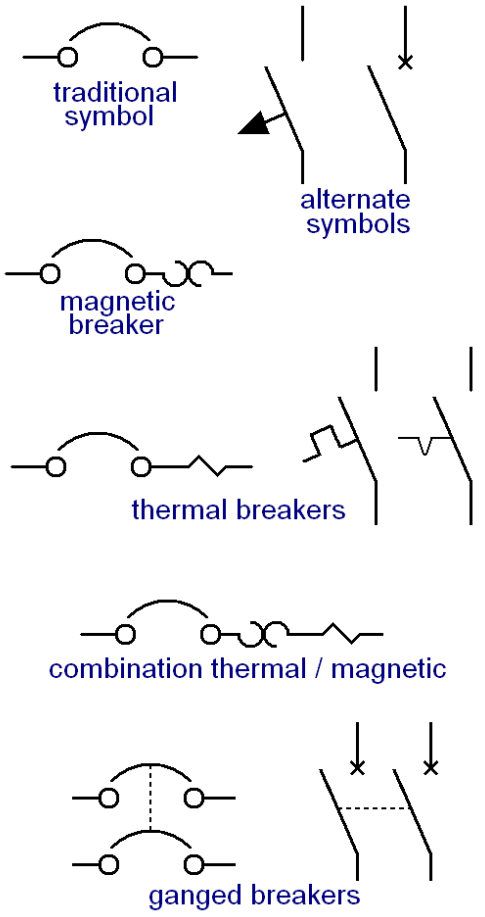
Decibel reference levels:

- 0dBW 1 watt
- 0dBkW 1kW
- 0dBm 1mW (0.78V in a 600W circuit)
- 0dBV 1V
- 0dBmV 1mV
- 0dBu about 0.78V
- +4dBu about 1.23V

Cable impedance:

- Video coax: 75Ω
- Other RF coax: 50Ω
- Twinlead: 300Ω
- Twinax: 100ΩUTP and most digital: 100Ω

Breaker Symbols



25-pair UTP color code

FIRST COLOR IS BODY COLOR, SECOND COLOR IS STRIPE

pair	wire 1 (tip)	wire 2 (ring)	pair	wire 1 (tip)	wire 2 (ring)
1	white-blue	blue-white			
2	white-orange	orange-white	16	yellow-blue	blue-yellow
3	white-green	green-white	17	yellow-orange	orange-yellow
4	white-brown	brown-white	18	yellow-green	green-yellow
5	white-gray	gray-white	19	yellow-brown	brown-yellow
6	red-blue	blue-red	20	yellow-gray	gray-yellow
7	red-orange	orange-red	21	violet-blue	blue-violet
8	red-0green	green-red	22	violet-orange	blue-orange
9	red-brown	brown-red	23	violet-green	blue-green
10	red-gray	gray-red	24	violet-brown	blue-brown
11	black-blue	blue-black	25	violet-gray	blue-gray
12	black-orange	orange-black			
13	black-green	green-black			
14	black-brown	brown-black			
15	black-gray	gray-black			

End of Chapter 11

EM5 PRACTICE EXAMS

CHAPTER 1 – SOLDERING

1. Traditional solder is made of:
   A. lead
   B. copper
   C. tin and lead
   D. zinc

2. The special characteristic of eutectic solder is:
   A. it does not give off fumes
   B. there is a temperature range where it is "mushy"
   C. it has a rosin core
   D. it is the tin-lead alloy that melts at the lowest temperature

3. The composition of eutectic solder is:
   A. 63% tin, 37% lead
   B. 56% tin, 44% lead
   C. 63% lead, 37% tin
   D. 90% tin, 10% lead

4. The traditional solder most used in electronics is made of:
   A. 40% tin, 60% lead
   B. 60% tin, 40% lead
   C. 75% tin, 25% lead
   D. 60% tin, 40% antimony

5. When a liquid solder joint is cooling,
   A. you should blow on it
   B. you should wiggle it to be sure solder gets into every crevice
   C. it must be held still
   D. you should pinch it with a heat sink clamp to draw off heat

6. Lead-free solder is mostly:
   A. antimony
   B. copper
   C. tin
   D. silver

7. Before a soldering tip is first used, it must be:
   A. scraped with a file
   B. oiled
   C. tinned
   D. demagnetized

8. During soldering, _____ is used to remove oxide.
   A. rosin (or equivalent) flux
   B. acid flux
   C. steel wool
   D. scouring powder

9. In a proper solder joint, the solder _____ the metal parts of the joint.
   A. makes contact with
   B. wets and alloys with
   C. replaces
   D. corrodes

10. A solder joint where the solder does not wet all surfaces is called a:
   A. cold solder joint
   B. point-contact joint
   C. asymmetrical joint
   D. surface-mount

11. A soldering iron holder should:
   A. draw heat away from the iron
   B. demagnetize the iron
   C. confine the smoke from the tip
   D. enclose the iron and be tip-resistant

12. With time and use, a copper tip will:
   A. magnetize
   B. become plated with lead
   C. pit
   D. bend out of shape

13. The advantage of an iron-coated tip is:
   A. it will work at higher temperatures
   B. it does not pit and lasts longer
   C. it does not magnetize
   D. it requires less solder per joint

14. Most soldering guns use _____ to produce heat.
   A. high current at the tip
   B. a magnetic field
   C. capacitive reactance
   D. high resistance

15. The most important soldering gun maintenance task is:
   A. periodically spraying the trigger switch contacts with contact cleaner
   B. tightening the tip connections
   C. scraping crud off the tip using steel wool
   D. periodically demagnetizing

16. When soldering, solder should first be applied to:
   A. the point where the tip meets the work
   B. the tip, away from the work
   C. the work, on the side away from the tip
   D. the tip, before the tip is touched to the work

17. Solder does not need to be applied during soldering if:
    A. enough flux is used
    B. the soldering tip is well tinned
    C. enough heat is used
    D. all parts are heavily pre-tinned

18. A clip-on heat sink is used to:
    A. hold the work steady
    B. protect the joint from excessive heat
    C. protect parts from excessive heat
    D. keep the iron from overheating

19. A metal that cannot be soldered using the usual techniques is:
    A. copper
    B. aluminum
    C. iron
    D. brass

20. When soldering CMOS components, the following is not one of the recommended precautions:
    A. ground the iron
    B. ground the tech through a 1M resistor
    C. ground the bench lamp
    D. ground the bench top through a 1M resistor

21. SMT components are typically soldered using:
    A. acid core solder
    B. solder paste
    C. solder containing antimony
    D. a soldering gun

22. Which of the following desoldering methods should never be used?
    A. vacuum
    B. braided wick
    C. air pressure
    D. bumping a PC board on the bench top

23. If it is necessary to have a flammable solvent near a soldering iron, it should be contained in:
    A. a push-top dispenser
    B. a glass container
    C. a metal container
    D. a solvent-soaked rag

24. A soldering tip is cleaned by:
    A. shaking excess solder into a wastebasket
    B. wiping on a damp sponge
    C. scraping with a file
    D. wiping with a dry paper towel

CHAPTER 2 – ELECTRICAL CONDUCTORS

1. The reason there's a limit to maximum current through a given wire is:
    A. the wire has resistance
    B. the wire has capacitance
    C. the wire has inductance
    D. the wire has a magnetic field

2. resistivity is:
    A. the per-cubic-foot resistance of a material
    B. the per-foot resistance of a 12-gauge wire made of a particular material
    C. the per-cubic-meter resistance of a material
    D. the per-meter resistance of a 12-gauge wire made of a particular material

3. Voltage drop is:
    A. the voltage between a wire and ground
    B. the voltage difference between the ends of a wire
    C. the voltage across a pair of wires
    D. the voltage between a wire and the outside surface of its insulation

4. Voltage drop is determined by:
    A. the voltage on a wire and its resistance
    B. the wire's resistance and the current it's carrying
    C. the wire's resistance divided by voltage
    D. the voltage on a wire times the current it's carrying

5. Power loss in a wire is:
    A. voltage drop X resistance
    B. resistance X voltage
    C. resistance X current
    D. voltage drop X current

6. The two most common wire materials are:
    A. copper, steel
    B. copper, aluminum
    C. aluminum, silver
    D. copper, silver

7. What keeps aluminum wire from being used more often is:
    A. it's expensive
    B. it's too stiff to work with
    C. it corrodes easily
    D. it cannot be soldered, it exhibits cold creep

8. For long-distance, high-voltage power transmission, the most common type of wire is:
   A. pure copper
   B. copper conductor, aluminum reinforcement
   C. aluminum conductor, steel reinforcement
   D. Litz wire

9. The relationship between a wire's resistance and length is:
   A. directly proportional
   B. inversely proportional
   C. a square function
   D. there is no relation

10. The relationship between a wire's resistance and its cross-sectional area is:
   A. proportional
   B. proportional to the square of area
   C. inversely proportional
   D. inversely proportional to the square of the area

11. In American Wire Gauge, a larger gauge number means _____ wire.
   A. smaller diameter
   B. larger diameter
   C. longer
   D. shorter

12. According to the fire code, an AC branch circuit with a 20-amp breaker requires:
   A. no. 14 wire
   B. no. 12 wire
   C. no. 10 wire
   D. 3/0 wire

13. A 250kcmil wire is:
   A. 250,000 mils in diameter
   B. equivalent to 250,000 1-mil wires in parallel
   C. 250,000 mils in circumference
   D. the square root of 250,000 mils in diameter, or about 500 mils

14. Aluminum has about ____ times the resistivity of copper.
   A. 3
   B. 2.6
   C. 1.2
   D. 1.6

15. Resistivity of copper wire _____ when temperature rises
   A. falls by about 0.22% per degree F
   B. is not affected
   C. rises by about 0.4% per degree F
   D. rises by about 0.22% per degree F

16. Stranded wire should be used where:
   A. maximum current carrying ability is needed
   B. the ends will be soldered
   C. the wire will be flexed a lot
   D. voltage will be extremely high

17. Rubber insulation is used:
   A. at extremely high temperatures
   B. at extremely high currents
   C. where the wire will be flexed a lot
   D. at extremely low temperatures

18. PTFE (Teflon®) insulation is used where:
   A. the insulation must be fireproof
   B. the insulation must be slippery (for pulling thru conduit)
   C. the wire will need to bend around sharp corners
   D. the wire must be completely nonmagnetic

19. The main limitation on the use of PVC insulation is:
   A. it's expensive
   B. it burns and emits noxious fumes in a fire
   C. it's hard to strip
   D. markings and color bands fade with time

20. In a commercial building, where a wire runs vertically between floors, __-rated wire should be used.
   A. X
   B. R
   C. P
   D. Q

21. A plenum is:
   A. the space above a ceiling, when used as an air conduit
   B. the space inside a wire conduit
   C. the space inside a breaker box
   D. the area around an outdoor wire

22. Skin effect causes current in a wire to be:
   A. slowed down
   B. concentrated in the core
   C. swirled around in a spiral
   D. pushed toward the surface

23. The purpose of Litz wire is to:
   A. lower DC resistance
   B. prevent skin effect
   C. protect against fire
   D. reduce inductive reactance in a wire pair

24. A cable is:
    A. two or more wires bundled together
    B. a stranded wire
    C. a solid wire
    D. Litz wire

25. In coaxial cable,
    A. a pair of signal wires run side by side
    B. the signal wire is surrounded by a shield.
    C. the shield is always braided wires
    D. the signal conductor is always stranded

26. Crosstalk is:
    A. unwanted signal coupling from one wire or cable to another
    B. 60Hz hum induced in a wire or cable
    C. radio interference induced in a wire or cable
    D. unwanted signal coupling from a signal wire to shield

27. When UTP cable is used, crosstalk is prevented by:
    A. tinning the wires
    B. using PTFE insulation
    C. using balanced signals
    D. using unbalanced signals (one side grounded)

28. Twisting a pair of wires:
    A. greatly reduces high frequency loss
    B. reduces voltage drop
    C. improves interference & crosstalk rejection
    D. makes a cable stronger

CHAPTER 3 – GENERATORS

1. “Electromagnetic induction” means:
    A. voltage induced in a wire by a constant magnetic field
    B. voltage induced in a wire by a changing magnetic field
    C. voltage induced in a wire by inductive flyback
    D. voltage induced in a wire by capacitive cross-coupling

2. In Fleming's rule, thumb, first finger and center finger represent:
    A. twist, field and current
    B. thrust, force and current
    C. thrust, field and current
    D. thrust, force and capacitance

3. For generators, the right-hand rule is used with:
    A. electron flow
    B. either conventional or electron flow
    C. conventional current
    D. there is no right hand rule

4. A prime mover is:
    A. the transmission line coming out of a power plant
    B. the original source of energy in a generating system
    C. the largest motor in a factory
    D. the motor in an electric car

5. Voltage created in a generator always starts out as:
    A. DC
    B. AC
    C. high frequency
    D. intermittent

6. In a generator, the part that moves is called the:
    A. armature
    B. field
    C. stator
    D. rotor

7. In a generator, the part that does not move is called the:
    A. field
    B. rotor
    C. armature
    D. stator

8. The mechanism that makes electrical contact with the rotor in an AC generator is the:
    A. slip ring assembly
    B. bearings
    C. stator
    D. commutator

9. In a traditional DC generator, AC is turned into DC by the:
    A. slip rings
    B. commutator
    C. armature
    D. stator

10. In a generator, the part where voltage is induced is the:
    A. stator
    B. field
    C. slip rings
    D. armature

11. The sliding pieces that make electrical contact with the slip rings are called:
    A. brushes
    B. bearings
    C. brake pads
    D. commutators

12. A magneto is a generator:
    A. with a stationary armature
    B. where the field is supplied by permanent magnets
    C. with a self-excited field
    D. with many poles

13. Excitation current is:
    A. stray current induced in the generator frame
    B. current used to magnetize a transformer
    C. current used to magnetize the armature
    D. current used to magnetize the field

14. Self-excitation is:
    A. using part of the generator's own output to create the field
    B. using permanent magnets to create the field
    C. using part of the output of the field to magnetize the armature
    D. using a separate small generator to magnetize the field

15. A generator where the armature and field coils are connected in series is:
    A. a compound-wound generator
    B. a series-wound generator
    C. a DC generator
    D. an AC generator

16. When the electrical load on a series generator is increased, output voltage:
    A. increases a lot
    B. stays the same
    C. decreases
    D. slowly decreases to zero

17. A generator where the armature and field coils are connected in parallel is:
    A. a compound generator
    B. a magneto
    C. a parallel-wound or shunt-wound generator
    D. self-excited

18. When the electrical load on a parallel generator is increased, output voltage:
    A. decreases a little
    B. greatly decreases
    C. increases slightly
    D. varies unpredictably

19. A generator using both series and parallel wiring is:
    A. a compound generator
    B. a DC generator
    C. an AC generator
    D. self-excited

20. When the electrical load on a series/parallel generator increases, output voltage:
    A. increases
    B. decreases
    C. stays fairly stable
    D. slowly sags to zero

21. An AC generator's output frequency depends on:
    A. speed and number of windings in the armature
    B. number of armature windings and strength of the field
    C. distance between rotor poles and stator poles
    D. speed and number of poles

22. A three phase generator puts out:
    A. 3 sine waves, 90° apart
    B. 3 sine waves, 120° apart
    C. 3 sine waves at 3 different voltages
    D. 3 sine waves whose phase varies linearly with load

23. In a delta system, each winding is connected:
    A. across two phases
    B. between a phase and ground
    C. between the rotor and stator
    D. between the armature and field

24. In a wye system, each winding is connected:
    A. across two phases
    B. between a phase and ground
    C. in series with one phase
    D. all 3 are wired in parallel

25. Faraday's law states that output voltage varies with:
    A. number of windings, number of poles
    B. number of poles, speed of rotation
    C. strength of field, number of poles
    D. number of windings, speed of rotation

CHAPTER 4 – MOTORS

1. Fleming's left hand rule for motors is used with:
   A. AC motors only
   B. DC motors only
   C. electron flow
   D. conventional current

2. Which of the following is not a characteristic of a series-wound motor?
   A. small size
   B. stable speed
   C. large starting torque
   D. turns the same direction regardless of voltage polarity

3. In a shunt-wound motor, _____ limits maximum speed.
   A. back voltage
   B. a mechanical governor
   C. bearing friction
   D. air drag

4. The usual way of changing the speed of a DC motor is:
   A. change the magnetization of the field
   B. change the supply voltage
   C. attach a variable brake
   D. change the number of windings in the rotor

5. Most DC motors can be braked by:
   A. turning off the power and shorting the wires
   B. feeding AC into them
   C. turning off the power and leaving the wires unconnected
   D. demagnetizing the field

6. A universal motor works on:
   A. 120, 240 or 480VAC
   B. 12VDC or 120VAC
   C. AC or DC
   D. any voltage

7. A brushless AC motor uses _____ to start the rotor turning.
   A. a pulley
   B. a rotating field
   C. a pulsating field
   D. a stationary field

8. With a 60Hz AC source, a synchronous 2-pole motor will turn at:
   A. 7,200 RPM
   B. 1,800 RPM
   C. 360 RPM
   D. 3,600 RPM

9. A typical induction (non-synchronous) 2-pole motor running on 60Hz current and fully loaded typically turns at:
   A. 3,600 RPM
   B. 3,500 RPM
   C. 1,750 RPM
   D. 1,200 RPM

10. In an induction motor, the rotor is magnetized by:
   A. current through its coils, via slip rings
   B. permanent magnets
   C. current through its coils, via a commutator
   D. being inside the field

11. The difference between synchronous speed and actual speed in an induction motor is called:
   A. leakage
   B. slip
   C. drag
   D. shortage

12. In a single-phase motor, we make the rotor turn by:
   A. switching the rotor current on and off
   B. switching the field on and off
   C. creating a field external to the motor
   D. creating a second phase inside the motor

13. In a capacitor-run motor, the capacitor is there to:
   A. create a continuous 90° phase shift
   B. create a 90° shift while starting
   C. suppress RF interference
   D. correct the duty cycle

14. In a shaded pole motor, phase shift is created by:
   A. placing a shorting ring around part of each pole
   B. placing a shorting ring around all of each pole
   C. angling the copper bars in the squirrel cage
   D. making one pole bigger than the other

15. A split-phase motor creates a rotating field using:
   A. two capacitors
   B. two different kinds of coils positioned at right angles
   C. a single coil tapped in the middle
   D. two identical coils positioned at right angles

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16. a 4-pole motor will run at ____ a 2-pole motor.
    A. 4X the speed of
    B. the same speed as
    C. twice the speed of
    D. half the speed of

17. One electrical horsepower is:
    A. 525 watts
    B. 1,100 watts
    C. 746 watts
    D. 396 watts

18. When an overloaded motor slows down dramatically, that's called
    A. pullout
    B. de-synchronization
    C. mega-slip
    D. shifting gears

19. When a motor is stalled or just starting, its current draw is typically _____ its running current.
    A. 6 to 10 times
    B. 2 to 3 times
    C. about 1/2
    D. the same as

20. For most AC motors, the only practical way to vary the speed is:
    A. vary the mechanical load
    B. vary the AC power frequency
    C. vary the voltage
    D. vary the number of turns in the field winding

21. "Dynamic" braking of an AC motor is done by
    A. shorting the wires together
    B. putting DC across the power wires
    C. reversing the wire connections
    D. applying brake pads using electric solenoids

22. The thing a stepper motor can do, which other motors can't, is:
    A. spin at extremely high speed
    B. produce extreme torque
    C. run on any voltage
    D. stop and freeze in a particular position

23. In a permanent-magnet DC motor, rotation can be reversed by:
    A. reversing the DC polarity
    B. momentarily removing, then re-connecting the DC source
    C. changing connections on the field winding
    D. a permanent magnet DC motor cannot be reversed

24. A series, shunt, compound or universal motor can be reversed by:
    A. swapping armature and stator wires
    B. swapping armature or stator wires (not both)
    C. reconnecting a shunt motor as a series motor or vice versa
    D. these motors cannot be reversed without changing their internal construction

25. A 3-phase motor can be reversed by:
    A. changing the grounding point
    B. swapping any two power leads
    C. shifting all three leads to the next phase
    D. a 3-phase motor cannot be reversed

CHAPTER 5 – AC POWER GRID

1. Long distance power transmission is usually done at:
    A. 120 volts
    B. 480 volts
    C. several hundred kV
    D. several thousand volts

2. A motor-generator set is usually used to:
    A. filter electrical noise from the line
    B. step a high DC voltage down to a lower voltage
    C. store energy as rotational momentum
    D. provide isolation from lightning that may hit the high-voltage transmission lines

3. Delta voltages (across phases) are about ___ times wye voltages (between each phase and common).
    A. 0.65X
    B. 0.85X
    C. 1.7X
    D. 2.77X

4. A system with 480V delta is about ____ wye.
    A. 120V
    B. 208V
    C. 365V
    D. 277V

5. Which is not true of the delta design?
    A. both ends of each coil must be well insulated from ground
    B. the phases have a common point that may be grounded
    C. each coil is connected across two phases
    D. voltage across the coils is greater than in the wye design

6. “Secondary transmission” means:
   A.
   B. the voltage that comes out of the transformer secondary at the power plant
   C. the voltage that enters a home
   D. stepped down once from ultra-high voltage

7. Power drops are:
   A. wires feeding individual homes and businesses
   B. broken wires that touch the ground
   C. another expression for power outages
   D. power lost in the wires

8. 120 / 240V residential power is commonly called:
   A. 2-phase
   B. bi-phase
   C. primary distribution
   D. secondary transmission

9. Which of the following is *not* an advantage of DC ultra-high voltage transmission?
   A. comparatively low transmission loss
   B. interconnection of systems without worrying about phase
   C. no skin effect in wires
   D. easy conversion to 120VAC

10. What's one thing that happens when the 3 phases are not exactly 120° apart or exactly the same voltages?
   A. lights flicker
   B. motors run hot and produce less torque
   C. wires create an audible hum
   D. motor rotors become permanently magnetized

11. “Single phasing” occurs when:
   A. one phase drops out
   B. one phase gets out of position with respect to the others (is no longer 120°)
   C. a single-phase motor is connected to a 3-phase power source
   D. a capacitor-start motor's capacitor shorts out

12. A transient is:
   A. a momentary power outage
   B. a momentary power line voltage drop when a motor is starting
   C. the momentary short circuit when commutator sections are switching
   D. a spike of much higher voltage than the normal AC voltage on a wire

13. “Base load” is:
   A. the load on the output of a subscriber transformer
   B. the normal load on a power plant during a given period
   C. the lowest load in a given 24-hour period
   D. the highest load in a 24-hour period

14. “Peak load” is:
   A. the increased load when a motor is starting or stalled
   B. the load current that will trip a breaker
   C. the short-term heaviest load on a power plant during a given period
   D. current drawn at each peak of a 60Hz sinewave

15. One useful method of load shaving is:
   A. shifting some use to normally low-load times
   B. running large loads all the time
   C. reducing line voltage to 90V during peak load periods
   D. reducing the line frequency to 50Hz during peak load periods

16. When a load has a poor power factor:
   A. voltage is unstable
   B. voltage and current are out of step
   C. current is unstable
   D. lights flicker

17. The usual method of improving power factor is:
   A. adding more resistive loads
   B. connecting to a different tap on the substation transformer
   C. keeping small generators running that can be used to assist the main generator
   D. connecting capacitors or inductors (depending on the situation) across the power line

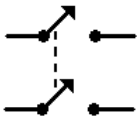
18. The power density of sunlight at noon on a clear day is around:
   A. 100W per square meter
   B. 1kW per square meter
   C. 1kW per square foot
   D. depends greatly on lattitude

19. A good solar panel turns about ___ of sunlight into electricity.
   A. 10%
   B. 25%
   C. 55%
   D. 70%

20. Microgeneration means:
    A. any generator under 1MW
    B. low-voltage generation, e.g. 12V
    C. generating electricity in many locations
    D. generating very high frequency AC

CHAPTER 6 – CIRCUIT CONTROLS AND PROTECTION

1. The switch illustrated is:



    A. SPST
    B. DPST
    C. SPDT
    D. DPDT

2. Switches in high-current circuits should be :
    A. physically large
    B. slider type
    C. snap type
    D. multi-pole

3. If a high-current switch is used in a low-current circuit,
    A. it will work fine for a long time
    B. contacts may oxidize and become unreliable
    C. the signal waveform will be distorted
    D. contacts may not completely close

4. A pushbutton labeled “NC” is:
    A. latching action
    B. alternating action
    C. an open circuit when you’re not pushing it
    D. a closed circuit when you’re not pushing it

5. Another name for alternating pushbutton action is-
    A. push-on, push-off
    B. A-B
    C. lockout
    D. remote

6. A momentary NO 2-position SPST switch would be labeled:
    A. (OFF)-ON
    B. OFF-ON
    C. (OFF)-(ON)
    D. OFF-(ON)

7. Which of the following is not an effective way to prevent accidental operation?
    A. use a switch with a lockout
    B. use a switch with a cover over it
    C. use two switches connected in series
    D. use a large, stiff switch

8. When installing crimp connections, the most important consideration is:
    A. to insulate the entire connector after crimping
    B. crimp hard enough to create a cold weld
    C. to strip the insulation back far enough that about ¼ inch of bare wire sticks out of the lug
    D. to use a lug with the same color sleeve as the wire insulation

9. The part of a relay that moves is called the:
    A. stator
    B. pole piece
    C. armature
    D. coil

10. A contactor is:
    A. a multipole relay
    B. a solenoid-type relay
    C. an AC-operated relay
    D. a low-current relay

11. A limitation of solid-state relays is:
    A. the “contacts” may be AC or DC only
    B. they take a lot of current to operate
    C. they’re larger than mechanical relays
    D. they create RF interference

12. What blows a fuse is:
    A. excessive ambient temperature
    B. excessive power
    C. excessive voltage
    D. excessive current

13. When a unit is working normally, voltage drop across its fuse is:
    A. almost zero
    B. the same as the supply voltage
    C. half the supply voltage
    D. anything between zero and the supply voltage, depending on conditions

14. A fuse’s voltage rating identifies:
    A. minimum operating voltage
    B. together with current, the maximum power level
    C. the highest-voltage circuit the fuse can safely be used in
    D. the voltage the fuse was tested on at the factory

15. When a fuse is enclosed in a cartridge holder, its rated current is reduced to about _____ of the current marked on the fuse.
    A. 35%
    B. 75%
    C. 50%
    D. the rating does not change

16. After a fuse blows, _____ appears across it.
    A. the entire supply voltage
    B. zero volts
    C. half the supply voltage
    D. cannot be predicted

17. A fuse labeled F6,25AL250V would be:
    A. 625A, low breaking capacity, 250VAC maximum
    B. 6.25A, low breaking capacity, 250VAC maximum, fast blow
    C. 6.25A, low breaking capacity, 250VDC maximum, fast blow
    D. fast blow, 6,250 amps, average breaking capacity, low temperature, 250VAC maximum

18. The main difference between a fuse and a breaker is:
    A. a breaker is cheaper
    B. a breaker is smaller
    C. a breaker only works with AC
    D. a breaker can be reset and used again

19. Breakers in AC breaker boxes are usually:
    A. thermal
    B. combination thermal and magnetic
    C. magnetic
    D. DC

20. A breaker that uses a bimetallic strip or disc is a:
    A. thermal breaker
    B. magnetic breaker
    C. a capacitive breaker
    D. a combination thermal-magnetic breaker

21. Breakers are sometimes ganged together to:
    A. increase reliability
    B. increase current-carrying ability
    C. break 2 or 3 phases at the same time
    D. increase maximum voltage

22. This symbol identifies:

    A. a thermal breaker
    B. a magnetic breaker
    C. a self-resetting breaker
    D. an arc-detecting breaker

23. A ground-fault-interrupt trips when:
    A. the common (white) wire is an open circuit
    B. outgoing current is different from incoming current
    C. the ground (green) wire has a poor connection
    D. the ground (green) wire is shorted to one of the others

24. An arc-sensing breaker:
    A. breaks when it detects that an arc lamp is plugged into the circuit
    B. breaks when it detects high-frequecy energy on the wires
    C. is the only acceptable type for an arc welder
    D. is not legally required in any jurisdiction

25. A current-limited source cannot put out:
    A. more than 1A
    B. AC
    C. DC
    D. enough current to start a fire

CHAPTER 7 – INTERFACING ELECTRONIC PRODUCTS – LEVELS & IMPEDANCES

1. A signal gets weaker as it moves through a cable. This is called:
    A. attenuation
    B. reflection
    C. oxidation
    D. decimation

2. _____ suffer the greatest loss in a cable.
    A. low frequencies
    B. DC control voltages
    C. high frequencies
    D. digital data

3. The formula for wavelength is:
    A. wavelength = frequency / speed
    B. wavelength = speed / frequency
    C. speed = wavelength / frequency
    D. frequency = wavelength / speed

4. In air and space, electrical signals travel at about _____ .
    A. 3×10^8 meters per second
    B. 10^8 meters per second
    C. 186,000 meters per second
    D. 3×10^8 miles per second

5. “Impedance matching” means the impedances of sending unit, cable and receiving unit are all:
   A. 50Ω
   B. 75Ω
   C. 600Ω
   D. the same

6. Impedances are usually not matched in:
   A. audio
   B. video
   C. data
   D. master antenna systems

7. Impedance conversion is usually done using:
   A. a capacitor
   B. a transformer
   C. a short length of cable shorted at the end
   D. a conversion amplifier

8. A transformer that converts between a balanced signal and an unbalanced one is usually called:
   A. a balun
   B. an unbalancer
   C. bipolar
   D. differential

9. A cable shield should be connected to:
   A. Earth ground
   B. nothing, left floating
   C. a power outlet ground
   D. equipment chassis

10. If a signal’s strength normally varies, as in audio, the range of variation is called:
   A. level instability
   B. dynamic range
   C. volume range
   D. volume units

11. A reference level is:
   A. a specific level that other levels are compared against
   B. the actual level at an input or output
   C. always referred to 1V
   D. always referred to 1mW

12. In audio, the professional reference line level is:
   A. 0dBW, 1 watt
   B. 0dBm, one milliwatt
   C. 0dBV, one volt
   D. 0dBu, about 0.78V

13. In audio, “line level” is generally in the range of:
   A. one millivolt AC
   B. one volt AC
   C. one volt DC
   D. one watt

14. Microphone level is:
   A. usually much higher than line level
   B. usually much lower than line level
   C. about the same as speaker level
   D. about the same as headphone level

15. “Pad” is another name for:
   A. attenuator
   B. amplifier
   C. equalizer
   D. filter

16. A _____ microphone has a built-in preamplifier and requires DC power.
   A. dynamic
   B. telephone handset
   C. condenser
   D. directional

17. Headroom is the difference between normal “maximum” signal level and:
   A. the noise floor
   B. clipping or overload level
   C. lowest signal level
   D. average level

18. AGC means:
   A. automatic gain control
   B. automatic gain compensation
   C. audio gain control
   D. average gain correlation

19. In analog, “compression” means:
   A. reducing a signal’s dynamic range
   B. lowering the level
   C. reducing the frequency spectrum
   D. shortening the length of the program

20. The standard baseband video level is approximately:
   A. 1mW
   B. 1V P-P
   C. 1mV P-P
   D. 1V RMS

21. Another name for ‘balanced pair” is:
   A. stereo pair
   B. differential pair
   C. impedance-matched pair
   D. proportional pair

22. In RS232, voltage levels for “1” and “0” may be as high as:
   A. +5V
   B. -5V
   C. + and -9V
   D. + and -25V

23. The four wires of a USB cable are:
    A. +5V, ground, differential pair for data
    B. +12V, ground, differential pair for data
    C. +5V, ground, send, receive
    D. +5V, send, receive, synchronization

24. The unusual feature of MIDI is:
    A. it operates at very high speed
    B. it uses more than two digital levels
    C. audio is mixed with digital
    D. send and receive units are electrically isolated

25. MIDI and LVDS signals exist as:
    A. voltage levels
    B. current levels
    C. sine waves
    D. triangle waves

26. 4- to 25-mA current loops are most often used by
    A. audio control systems
    B. sensors in industrial systems
    C. video systems
    D. high speed data systems

27. The level of electrical noise that's always present in every system is called:
    A. the reference level
    B. +4dBu
    C. the noise floor
    D. the clipipng level

28. White noise has equal energy in every _____ frequency span.
    A. decade
    B. absolute (linear)
    C. proportional (logarithmic)
    D. 2:1

29. Pink noise has equal energy in every _____ frequency span.
    A. 1Hz
    B. absolute (linear)
    C. proportional (logarithmic)
    D. 1MHz

30. In a 50Ω system, the noise contained in each Hz of spectrum is roughly:
    A. 1mV
    B. 1μV
    C. 1nV
    D. 1μW

CHAPTER 8 – INTERFACING ELECTRONIC PRODUCTS – CABLES AND CONNECTORS

1. When stripping a wire end, the most important thing is:
    A. make it quite a bit longer than necessary
    B. twist the stripper while moving it
    C. don't nick the conductor
    D. clean up the insulation ends afterward

2. When stripping varnish off a wire:
    A. tilt the knife away from the wire end
    B. tilt the knife toward the wire end
    C. use the edge of a screwdriver
    D. use a butane lighter

3. The only acceptable kind of flux that is acceptable in electronics is:
    A. alkalai
    B. plastic
    C. acid
    D. rosin

4. Stranded wire ends should not be tinned (other than factory tinning) if they're going to be:
    A. clamped or squeezed
    B. wrapped around a solder terminal
    C. carrying very high voltage
    D. carrying very high frequencies

5. When connecting a braided shield,
    A. twist them around the conductors
    B. be sure there are no flyaway strands
    C. strip at least two inches
    D. tin the strands all the way to the jacket

6. The purpose of a drain wire is:
    A. to correct impedance variations
    B. to provide for DC power
    C. so you don't have to connect to the foil
    D. to cancel magnetic fields

7. The main purpose of a cable tiedown near a connector is:
    A. to create a neat installation
    B. to be sure the connector doesn't fall out
    C. to prevent cable flexing at the connector
    D. to create a shorted inductive loop

8. A drip loop:
    A. keeps collected water from dripping on the floor
    B. keeps water from running into the connector
    C. keeps water from upsetting the cable impedance
    D. is unnecessary

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9. From front to back, the parts of a 3-circuit phone plug are:
   A. tip, sleeve, ring
   B. plus, ground, minus
   C. tip, ring, sleeve
   D. left, ground, right

10. The bump on the side of a dual banana plug indicates:
   A. safety
   B. the larger pin
   C. hot (signal)
   D. ground

11. True or false: a twisted-wire splice must be soldered to be reliable
   A. false
   B. true
   C. depends on the kind of wire
   D. depends on the kind of signal

12. A special virtue of the Western Union splice is:
   A. it has low inductance
   B. it does not need soldering
   C. it's hard to pull apart
   D. it's the easiest splice to make

13. One benefit of a ribbon cable is:
   A. you don't have to strip the wire ends with an IDC connector
   B. there is very little crosstalk
   C. very little signal is radiated
   D. it's almost immune to interference pickup

14. When two wire pairs are inserted into a 6P4C connector, pair 1 goes to:
   A. one end, pins 1 and 2
   B. the intermediate pins, 2 and 5
   C. the outer pins, 1 and 6
   D. the center pins, 3 and 4

15. A properly crimped lug forms ____ with the wire:
   A. a solder connection
   B. a temporary, easily removed connection
   C. a cold weld
   D. an electrically shielded connection

16. A stranded wire inserted into a Phoenix connector:
   A. should be tinned first
   B. should not be tinned first (factory tinned is okay)
   C. must be aluminum wire
   D. should not be stripped (the connector will pierce the insulation)

17. In a phone plug, the shield connects to the:
   A. tip
   B. sleeve
   C. ring
   D. the shield should not be connected

18. In an XLR plug, pin ____ is shield / ground.
   A. 1
   B. 2
   C. 3
   D. the ground lug connected to the shell

19. A phono plug is also called:
   A. a phone plug
   B. a modular plug
   C. a BNC plug
   D. an RCA plug

20. When plugging in a phono plug,
   A. the shell makes contact first
   B. the signal pin makes contact first
   C. the line is briefly shorted
   D. an impedance mismatch occurs

21. When installing a PL259 connector on RG8 or RG9 cable, the shell is _____ the braid.
   A. anchored to the shield by a setscrew
   B. clamped to
   C. screwed on over
   D. insulated from

22. Standard N, BNC and TNC connectors are good to:
   A. 10GHz or better
   B. 1GHz or better
   C. no higher than 150MHz
   D. 10MHz

23. The difference among N, BNC and TNC plugs is:
   A. the diameter of the signal pin
   B. the diameter of the inner shell
   C. how they attach to the cable
   D. how they attach to the jacks

24. In the telephone color code, the first UTP pair is:
   A. white, red
   B. white, blue
   C. red, black
   D. brown, red

25. Mass termination techniques are typically used with:

A. coax cable
B. unbalanced lines
C. ribbon cable
D. litz wire

26. In a MIDI link, the current loop wires are connected to:

A. pins 4 and 5
B. pins 1 and 2
C. pins 2 and 3
D. pin 3 and shell

CHAPTER 9 – MAKING MEASUREMENTS

1. Another name for "multimeter" is:

A. root-mean-square (RMS) meter
B. ammeter
C. volt-ohmmeter (VOM)
D. frequency meter

2. A VOM measures, at the minimum:

A. continuity, transistor gain
B. voltage, current, resistance
C. capacitance, resistance
D. voltage, inductance

3. The HOLD button, if a VOM has one,

A. keeps an auto-ranging meter from switching ranges
B. prevents the user from dropping the meter
C. keeps the voltage in the circuit the meter is attached to from changing
D. captures a reading and continues to display it

4. To measure a voltage, the meter is connected _____.

A. so the current flows through it
B. between the +DC voltage and Earth ground
C. between the signal input and output pins
D. across the voltage to be measured

5. "Meter loading" refers to:

A. how much a meter weighs
B. the way a meter affects the quantity being measured
C. how much voltage a meter can handle before overload
D. how much current a meter can handle before overload

6. To measure current by the direct method, the meter is connected _____

A. so the circuit current flows through it
B. between chassis ground and Earth ground
C. across the load
D. across the + and – power supply points

7. To measure current by the indirect method, a _____ is first connected _____.

A. low-value resistor, across the load
B. high-value resistor, across the load
C. low-value resistor, in series with the load
D. high-value resistor, in series with the load

8. The low-value resistor used in current measurements is called a:

A. shunt
B. pass
C. load
D. compensator

9. When measuring resistance, the unit under test must be

A. disconnected from everything else
B. Earth grounded
C. powered on
D. powered off

10. Testing a very-low-current fuse with an ohmmeter:

A. may blow the fuse
B. may give an inaccurate reading
C. presents a shock hazard
D. may damage the meter

11. When testing a diode, with the red lead connected to the anode:

A. the diode will heat up
B. the meter should show an 0.6V to 0.7V drop
C. the meter should show little or no conduction
D. the diode will be damaged

12. When testing a diode, with the black lead connected to the anode:

A. the diode will heat up
B. the meter should show an 0.6V or 0.7V drop
C. the meter should show little or no conduction
D. the diode will be damaged

13. To verify that a 12V car battery is fully charged, the ___ range below would be appropriate.
    A. 2VDC
    B. 20VDC
    C. 200VDC
    D. 200VAC

14. When using an autoranging meter, a tech must:
    A. take care not to apply too high a voltage
    B. pay special attention to which range the meter has chosen
    C. give the meter 15 seconds to settle
    D. not use the hold button

15. For most digital meters, when measuring a low resistance you must remember to:
    A. not hold the leads on for too long
    B. not put your fingers on the resistor body
    C. swap the leads, i.e. measure both ways
    D. subtract the resistance of the test leads

16. When using the separate high-current connection (e.g. 10A), special caution is required because:
    A. you could be burned
    B. there's usually no fuse in that circuit
    C. high current measurement requires a special meter
    D. the high-current connection only works with AC

17. When a 2,000 ohms-per-volt analog meter is set to the 50V scale, its resistance (loading) is:
    A. 2,000 ohms
    B. 20,000 ohms
    C. 50,000 ohms
    D. 100,000 ohms

18. The only AC voltage a VOM can be trusted to measure accurately is:
    A. a 60Hz sine wave
    B. 60Hz (any waveform)
    C. a sine wave (any frequency)
    D. an audio signal

19. A non-sinewave AC voltage can be measured accurately using:
    A. a peak-reading meter
    B. an RMS-measuring meter
    C. an RMS-reading meter
    D. an inductance meter

20. A digital VOM may measure low AC voltages inaccurately because:
    A. it heavily loads the circuit
    B. there is a voltage drop in the test leads
    C. the meter takes too long to settle at the correct reading
    D. there's a diode in the circuit

21. With AC-powered test gear, the tech must beware of extra ground paths via:
    A. test leads
    B. the AC power plug
    C. the bench top
    D. cable shields

22. On an oscilloscope display, the vertical dimension represents:
    A. frequency
    B. time
    C. current
    D. voltage

23. On an oscilloscope display, the horizontal dimension represents:
    A. frequency
    B. time
    C. current
    D. voltage

24. The input circuit of a typical scope consists of:
    A. a 1M resistance and 30pf capacitance shunt
    B. a 10M resistance and 30pf capacitance shunt
    C. a 1M resistance in series with a 30pf capacitance
    D. a diode rectifier circuit

25. Setting a scope probe's switch to 10X attenuation::
    A. reduces the display height by 10:1
    B. reduces the input impedance by 10:1
    C. increases the display height by 10X
    D. increases capacitive loading by 10X

26. Probe calibration adjusts:
    A. DC voltage sensitivity
    B. width of trace vs. time
    C. high frequency response
    D. trigger voltage

27. The vertical range switch is used to accommodate:
    A. signals of different impedances
    B. signals of widely different voltages
    C. signals of widely different frequencies
    D. balanced (differential) vs. unbalanced signals

28. The horizontal range (sweep) switch is used to accommodate:
    A. signals of different impedances
    B. signals of widely different voltages
    C. signals of widely different frequencies
    D. balanced (differential) vs. unbalanced signals

29. The purpose of the trigger controls is to:
    A. make the displayed waveform stand still
    B. protect the scope circuitry
    C. protect the unit under test
    D. separate digital data from analog signals

30. The benefit of setting the scope to display several cycles of a waveform is:
    A. it's easier for the scope to display
    B. you can see small details more clearly
    C. you're less likely to miss things that don't happen every cycle
    D. it's easier on the scope

31. The purpose of an AC / DC input switch set to AC is:
    A. to inject some DC voltage into an AC signal
    B. to observe the AC waveform of a signal that has a large DC offset
    C. to filter out power supply ripple and display a pure DC voltage
    D. to filter out stray AC signals when displaying a DC voltage

32. A dual-trace scope can be set for a differential input by:
    A. Setting the sweep switch to X-Y
    B. Setting the A-channel to high sensitivity and the B-channel to low sensitivity
    C. Setting the A channel to DC and the B channel to AC
    D. Setting the B-channel to "invert"

33. A function generator puts out, at a minimum:
    A. sine, square and triangle waves
    B. sine, sawtooth and triangle waves
    C. sawtooth, rectangular and squaare waves
    D. 1AC, DC and digital data

34. A "vernier" is:
    A. the vertical position knob on a scope
    B. the fine horizontal sweep adjustment on a scope
    C. a kind of control knob that permits very fine adjustment
    D. a 19th century science fiction writer

35. In a linear pot, 50% rotation corresponds to _____ resistance
    A. 50%
    B. 70%
    C. 30%
    D. 10%

36. In a logarithmic pot, 50% rotation corresponds to _____ resistance
    A. 50%
    B. 70%
    C. 30%
    D. 10%

37. a rectangular wave is like a square wave except that:
    A. the + and – alternations are not the same height
    B. the duty cycle is not 50%
    C. the sides are slanted (voltage transitions are not instantaneous)
    D. they are two names for the same thing

38. A function generator may have an input that allows amplitude and frequency to be electrically varied. This is called:
    A. distortion
    B. convolution
    C. modification
    D. modulation

EM5 PRACTICE QUIZ ANSWERS

Chapter 1, Soldering

1.C 2.D 3.A 4.B 5.C 6.C 7.C 8.A 9.B 10.A 11.D
12.C 13.B 14.A 15.B 16.A 17.D 18.C 19.B 20.C
21.B 22.C 23.A 24.C

Chapter 2, Electrical Conductors

End of EM1 Practice Quiz

1.A 2.C 3.B 4.B 5.D 6.B 7.D 8.C 9.A 10C. 11.A
12.B 13.B 14.A 15.C 16.C 17.C 18.A 19.B 20.B
21.A 22.D 23.B 24.A 25.B 26.A 27.C 28.C

Chapter 3, Generators

1.B 2.C 3.C 4.B 5.B 6.D 7.D 8.A 9.B 10D. 11.A
12.B 13.D 14.A 15.B 16.B 17.A 18.C 19.A 20.A
21.D 22.B 23.A 24.B 25.D

Chapter 4, Motors

1.D 2.B 3.A 4.B 5.A 6.C 7.B 8.D 9.B 10.D 11.B
12.D 13.A 14.A 15.B 16.D 17.C 18.A 19.A 20.B
21.B 22.D 23.A 24.B 25.D

Chapter 5, AC Power Grid

1.C 2.B 3.C 4.D 5.B 6.D 7.A 8.A 9.D 10.B 11.A
12.D 13.B 14.C 15.A 16.B 17.D 18.B 19.B 20.C

Chapter 6, Circuit Controls & Protection

1.B 2.C 3.B 4.D 5.A 6.D 7.D 8.B 9.C 10.B 11.A
12.D 13.A 14.C 15.B 16.A 17.B 18.D 19.B 20.A
21.C 22.B 23.B 24.B 25.D 26.B 27.C 28.B 29.C
30.C

Chapter 7, Interfacing, Levels & Impedances

1.A 2.C 3.B 4.A 5.C 6.A 7.D 8.A 9.D 10.B 11.A
12.D 13.B 14.B 15.A 16.C 17.B 18.A 19.A 20.B
21.B 22.D 23.A 24.D 25.B

Chapter 8, Interfacing, connectors

1.C 2.B 3.D 4.A 5.B 6.C 7.C 8.B 9.C 10.D 11.B
12.C 13.A 14.D 15.C 16.B 17.B 18.A 19.D 20.B
21.C 22.A 23.D 24.B 25.C 26.A

Chapter 9, Making Measurements

1.B 2.D 3.B 4.A 5.C 6.A 7.C 8.A 9.D 10.A 11.B
12.C 13.B 14.B 15.D 16.B 17.C 18.A 19.B 20.D
21.B 22.D 23.B 24.A 25.A 26.C 27.B 28.C 29.A
30.C 31.B 32.D 33.A 34.C 35.A 36.C 37.B 38.D